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COMPUTER AND VOICE NETWORK MANAGEMENT THROUGH LOW EARTH ORBITING SATELLITES

by

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March 2006

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ABSTRACT

This thesis provides a multi-faceted approach to preliminary feasibility studies for using satellite networks within the Center of Network Innovation and Experimentation's (CENETIX) research programs, with particular emphasis on Low Earth Orbiting (LEO) Satellite network solutions. Our exploration of management techniques for remote sensor technologies employing low throughput rate LEO satellite links revealed methods that connectivity can be tested when the connection is idle. Research into available amateur radio satellite assets lead to testing Automated Position Reporting System (APRS) satellites and terrestrial networks for common operational picture development in large geographical areas either too remote for common infrastructure or affected by disasters. The expansion of CENETIX's research opportunities led us to explore DIRECWAY and iDirect technologies as methods for expanding the Tactical Network Topology (TNT) network, and to test Nemesis' new DIRECWAY functionality. Additionally, we explored potential communications usage for future satellites in The Office of the Secretary of Defense's TacSat program.

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LIST OF ACRONYMS

AAL5	Asynchronous Transfer Mode Application Layer 5
AFSK	Audio Frequency Shift Keying
AMSAT	Radio Amateur Satellite Corporation
APRS	Automated Packet Reporting System
ARES	Amateur Radio Emergency Service
ARPANET	Advanced Research Project Agency Network
ARRL	Amateur Radio Relay League
ASCII	American Standard Code for Information Interchange
ATM	Asynchronous Transfer Mode
bps	Bits Per Second
CENETIX	Center of Network Innovation and Experimentation
CFR	Code of Federal Regulations
COTS	Common Off The Shelf
CMOT	Common Management Information Protocol over TCP/IP
CPI	Common Part Interface
DC	Direct Current
DOD	Department of Defense
FCC	Federal Communications Commission
FM	Frequency Modulation
FSK	Frequency Shift Keying
GCCS	Global Command and Control System
GIG	Global Information Grid
GPS	Global Positioning System
HEMS	High-Level Entity Management System
HF	High Frequency
ICMP	Internet Control Management Protocol
IEEE	Institute of Electrical and Electronics Engineers
IGATE	Internet Gateway
IP	Internet Protocol
IRC	Internet Relay Chat
IRLP	Internet Radio Linking Project
ISO	International Organization for Standardization
ISS	International Space Station
JTF	Joint Task Force
LAN	Local Area Network
LEO	Low Earth Orbiting
LI	Length Indicator
LLC	Limited Liability Company
LLNL	Lawrence Livermore National Laboratory
LRV	Light Reconnaissance Vehicle
MDT	Mobile Display Terminal

MIB	Management Information Base
MIT	Massachusetts Institute of Technology
NASA	National Aeronautics and Space Administration
NCC	Network Control Center
NMO	New Motorola
NMS	Network-Management System
NOC	Network Operations Center
NPS	Naval Postgraduate School
NTIA	National Telecommunications and Information Administration
NTS	National Traffic System
NWS	National Weather Service
OES	Office of Emergency Services
OID	Object Identifier
OSCAR	Orbiting Satellite Carrying Amateur Radio
P3-E	AMSAT-Phase 3E
PDA	Personal Digital Assistant
PING	Packet Internet Grouper Program
POTS	Plain Old Telephone System
PPP	Point-to-Point Protocol
QOS	Quality of Service
RACES	Radio Amateur Civil Emergency Service
RAS	Remote Access Service
RF	Radio Frequency
RHIB	Rigid Hull Inflatable Boat
SCORE	Signal Communications by Orbiting Relay Equipment
SGMP	Simple Gateway Monitoring Protocol
SINCGARS	Single Channel Ground and Airborne Radio System
SIPRNET	Secret Internet Protocol Router Network
SMIB	Satellite Management Information Base
SMS	Short Message Service
SNMP	Simple Network Management Protocol
SSID	Service Set Identifier
TCP	Transmission Control Protocol
TNC	Terminal Node Controller
TNT	Tactical Network Topology
VHF	Very High Frequency
VPN	Virtual Private Network
UCSB	University of California, Santa Barbara
UDP	User Datagram Protocol
UHF	Ultra High Frequency
UI	Unnumbered Information
VMOC	Virtual Mission Operations Center
VOIP	Voice Over Internet Protocol

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I. INTRODUCTION

Since the beginning of the modern communications age, network managers have endeavored to develop effective management techniques for their systems – to monitor Quality of Service (QOS), to identify and troubleshoot faults, and to record network usage statistics in order to charge their customers. The introduction of data networks provided greater capabilities of collecting and manipulating management data, and even provided integrated capabilities to remotely alter network configurations of distant nodes. Operators of global networks like the Internet and the telephone system, along with smaller critical networks like military systems, feel the management challenge, especially when vital communications depend upon the network and lives are potentially at stake.

Challenges of network management are complicated when network administrators must depend on outside providers for network connectivity. Often, network management information of the leased links will not be shared with customers, and any information of the leased links must be derived. As technology develops, reliance on leased assets – particularly wireless solutions – will only escalate. In disasters where terrestrial networks are destroyed, or in military operations in undeveloped parts of the world, satellites become the only practical solution for reliable high-speed communications over large distances. Management information of satellite links, especially when using commercial assets, must be derived by the ground station nodes that are under the administrator's control.

The Naval Postgraduate School's Center of Network Innovation and Experimentation (CENETIX) realizes the importance of satellite communications. Starting with sensors that communicate through satellite telephone networks, requirements for satellite connectivity with the Tactical Network Topology (TNT) test bed continues to expand as the CENETIX experiment team expands operations beyond the campus and the Camp Roberts testing area. Additionally, disaster relief operations after Hurricane Katrina struck the Gulf Coast emphasized the necessity of incorporating satellite communications in deployment packages.

Satellite telephone networks used both in Hurricane Katrina relief operations and in the TNT test bed consist of constellations of Low Earth Orbiting (LEO) Satellites. Additionally, amateur radio LEO satellites are often launched by universities and private organizations in order to conduct experiments, and are available to the general amateur radio community to also conduct experiments. Understanding what these satellites can provide, how to manage data flowing through them, and how to better employ them in CENETIX experiments is the focus of the CENETIX Satellite Network Management team, and the topic herein.

A. LOW EARTH ORBITING SATELLITE HISTORY

Prior to 1958, high frequency radios were the only wireless method of communicating beyond line of sight. While communications are possible, high frequency (HF) communications requires shifts in frequency as ionospheric and solar conditions change throughout the day and the year. Additionally, the low frequency bandwidth designated as the usable frequency spectrum restricts the amount and type of communication that can pass in a given geographic location. Under normal line-of-sight propagation, very high frequency VHF and ultra high frequency UHF communications would require relays to travel similar distances. Tropospheric scattering of UHF frequencies is possible to extend distances, but may require extensive computer control and is subject to interference by other users.[1]

To solve the line-of-sight problems, researchers began to look to space for answers. Royal Air Force Electronics Officer Arthur Clarke wrote in 1945 of the potential of satellites relaying communications between geographically separated ground stations.[2] AT&T Labs began to explore the idea of satellites carrying telephone conversations in 1954.[3]

The satellite concept became reality as Sputnik I was launched in 1957 by the Soviet Union.[4] Sputnik's mission was more of a proof of concept, as its only payload

[1] "Troposcatter Propagation" [web page] (cited 21 JAN 06); available from World Wide Web @ http://www.radio-electronics.com/info/propagation/troposcatter/troposcatter.php

[2] David J. Whalen, "Communications Satellites: Making the Global Village Possible" [web page] (cited 21 JAN 06); available from World Wide Web @ http://www.hq.nasa.gov/office/pao/History/satcomhistory.html

[3] Ibid.

[4] Ibid.

was a beacon that transmitted a beep at regular intervals.[5] However, advances occurred rapidly, with the launch of SCORE (Signal Communications by Orbiting Relay Equipment) by the United States Department of Defense in 1958.[6] SCORE introduced a store-and-forward voice relay system, allowing non-real time messages to be sent anywhere in the world as the satellite passed over.[7] In August, 1960 the National Aeronautics and Space Administration (NASA) launched Echo 1, which was a passive satellite used to relay telephone and television signals.[8] Later the same year, the U.S. Army launched Courier 1B, which provided the first digital store and forward system and relayed teletype messages.[9] The year 1961 brought amateur radio operators into the space race, with the launch of OSCAR 1 (Orbiting Satellite Carrying Amateur Radio).[10] In 1962 AT&T's Telstar 1 was the first satellite to have transponders, which allowed the satellite to retransmit live signals.[11]

With the launch of the first geosynchronous satellite in 1963, government and commercial services stopped using LEO satellites for communications purposes.[12] While geostationary satellites required higher power from the ground station to complete the link, the ability to use the satellite continuously outweighed the distance concerns for awhile. However, as portable gear such as cellular phones and handheld computers became more popular, a desire developed to use these devices anywhere on the planet. While the cellular networks continue to increase their coverage areas, some companies once again began to look at the LEO satellite for the sake of proximity and the ability to decode weak signals from Earth. The downside of lower orbital altitude, and thus

[5] Roger D. Launius, "Sputnik and the Origins of the Space Age" [web page] (cited 21 JAN 06); available from World Wide Web @ http://www.hq.nasa.gov/office/pao/History/sputnik/sputorig.html

[6] "SCORE (Signal Communications by Orbiting Relay Equipment)" [web page] (cited 21 JAN 06); available from World Wide Web @ http://www.globalsecurity.org/space/systems/score.htm

[7] Ibid.

[8] "Satellite Fact Sheet: Echo 1" [web page] (cited 21 JAN 06); available from World Wide Web @ http://www.tbs-satellite.com/tse/online/sat_echo_1.html

[9] "Courier" [web page] (cited 21 JAN 06); available from World Wide Web @ http://www.fas.org/spp/military/program/com/courier.htm

[10] "A Brief History of Amateur Satellites" [web page] (cited 21 JAN 06); available from World Wide Web @ http://www.amsat.org/amsat-new/satellites/history.php

[11] "Satellite Fact Sheet: Telstar 1" [web page] (cited 21 JAN 06); available from World Wide Web @ http://www.tbs-satellite.com/tse/online/sat_telstar_1.html

[12] David J. Whalen.

intermittent coverage, was solved by introducing constellation of many satellites capable of continuous coverage. The Iridium satellite constellation began providing services in 1998, with Globalstar following in 2000.

B. TACSAT AND OTHER NETWORK IMPLEMENTATIONS

The Tactical Satellite (TacSat) initiative is a collaborative effort between the Department of Defense Office of Force Transformation and the Naval Research Laboratory. Their goal is the development of a tactical micro satellite system, with an emphasis on providing quick response imagery capabilities to a Joint Task Force (JTF) Commander for military operations. TacSat aims to integrate space assets into a single portal, empowering JTF Commander to request data based on needed payload capabilities, the area of interest, downlink location, time desired, and allowing the system to determine the best asset to fulfill the requirement.

TacSat-1 was deployed in 2005. It has several payloads that provide cross-platform specific emitter detection, visible, and infrared imaging. The TacSat-1 payload allows for machine-to-machine collaboration between air and space assets. Its specific emitter payload consists of an infrared imaging camera capable of providing resolution up to 850-m, and a visible camera which provides resolution up to 70-m.[13]

The Naval Research Lab provides program management, micro-satellite integration, and control of the TacSat mission and design. With the aid of NASA, the users will interface with TacSat via the Virtual Mission Operations Center (VMOC), a web portal available on the Secret Internet Protocol Router Network (SIPRNET).[14] In the VMOC, users will propose missions and retrieve products via a secure computing network instead of a ground control station.

The TacSat micro-satellite program is impressive and shows great potential for the use in future operations but there are other network implications. One such is will the VMOC be the only method of providing tasking to the satellite. In some cases SIPRNET access is not guaranteed to all operational users. The tactical users will have to make requests to their command and control element in order to gain access to TacSat. Another issue is for the TacSat program to be successful in a high demand environment

[13] C.M. Huffine, "Rapid Satellite Payload Development for TacSat-1" [web page] (cited 21 JAN 06); available from World Wide Web @ http://www.nrl.navy.mil/content.php?P=04REVIEW212

[14] Ibid.

where time is increasingly of the essence, it will require several satellites in orbit. Time can be further reduced if the satellites can communicate with each other, and relay data to and from the VMOC. .

C. HISTORY OF CENETIX AND THE TACTICAL NETWORK TOPOLOGY

The Tactical Network Topology (TNT) experiment series provides CENETIX the ability to conduct on-going experimentation of various networking technologies in tactical environments. Having started with a focus on utilizing ad hoc wireless networks in a military environment, TNT has since progressed to include an IEEE 802.16 backbone that stretches over 100 miles between Camp Roberts and the Naval Postgraduate School, numerous unmanned aerial vehicles, a light reconnaissance vehicle, a NPS based network operations center, a tactical network operations center, and other wireless mesh technologies.

The vision of CENETIX is to extend current TNT capabilities through global partnerships and to maintain the TNT test bed as a premier environment for Department of Defense network research. Modeling the Global Information Grid (GIG), TNT explores new frontiers in deployable self-organizing nodes and decision-making networks jointly with Lawrence Livermore National Laboratory (LLNL), Massachusetts Institute of Technology (MIT), Stanford University, University of California Santa Barbara (UCSB), and other academic and corporate partners.[15] Using unmanned aerial, underwater, and ground vehicles, CENETIX focuses on the advanced studies of Network Centric Warfare concepts, including emerging collaborative architectures for team communications, and sensor-to-shooter network solutions.[16] Immediate goals include providing flexible, deployable network integration and operating infrastructure for interdisciplinary studies of multiplatform tactical networks, Global Information Grid connectivity, collaborative technologies, situational awareness systems, multi-agent architectures, and management of unmanned sensor vehicle-decision maker self-organizing environments.[17]

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15 "Center of Network Innovation and Experimentation (CENETIX)" [web page] (cited 21 JAN 06); available from World Wide Web @ http://131.120.176.50/cenetix/

16 Ibid.

17 Ibid.

TNT experiments are conducted quarterly and until recently have been limited to Camp Roberts and the Naval Postgraduate School. In the near future, CENETIX experiments will expand geographically to include potential testing areas around the world.

D. SIMPLE NETWORK MANAGEMENT PROTOCOL

The Simple Network Management Protocol (SNMP) is the dominant network management protocol. Its history began with the development of the Advanced Research Project Agency Network (ARPANET). At the inception of the ARPANET, no network management tools were necessary since there were only a limited number of users. However, as the ARPANET grew, network troubleshooting became an increasingly complex issue. The first attempt to manage the network was the development of the Internet Control Management Protocol (ICMP). By using ICMP, users could determine the sources of network trouble by using an echo/echo-reply protocol later known as the Packet Internet Grouper program (PING). [18]

Through the 1980's, PING was an adequate tool to manage the network. As the ARPANET grew into the Internet during the 1990's, network operators discovered that PING in itself was not enough to troubleshoot an exponentially growing network, leading to the development of the Simple Gateway Monitoring Protocol (SGMP). Created in 1987, SGMP was the first step to create a robust network management tool for the larger Internet. SGMP's development and usage led to more increasingly functional network management tools, including the High-Level Entity Management System (HEMS), SNMP, and Common Management Information Protocol over TCP/IP (CMOT).[19]

From these three the Internet Advisory Board selected SNMP as the network management tool of choice. SNMP is an improved version of SGMP and has proven to be a robust network management tool. It functions by manipulating three key components: managed devices, agents, and network-management systems (NMS). A managed device is a node, such as a computer, router, switch, server, or printer that has an SNMP agent. SNMP agents are network-management software modules that reside

[18] William Stallings, <u>SNMP, SNMPv2, SNMPv3, and RMON 1 and 2</u>, (Reading: Addison-Wesley, 1999).

[19] Ibid.

within managed devices, which collect and store management information about the managed device and its connections and make this information available to NMSs upon request. A NMS executes applications that monitor and control managed devices, and provides the bulk of the processing and memory resources required for network management. For SNMP to function effectively there must be more than one NMS on any managed network.

E. SCOPE DEFINITION

The TNT network continues to solidify as a robust tactical network, with wireless links used for both short distance and long-haul communications. However, in a tactical environment, it may not be feasible to establish fixed wireless station assets in a war zone, as these sites will require security and will have a high susceptibility to jamming. Satellites provide an excellent alternative, but geosynchronous or geostationary orbit satellites are already in heavy use. Low-earth orbiting satellites may prove to become a valid solution.

While some companies such as Iridium have established constellations of satellites providing coverage 100% of the time over the entire globe, tactical military satellites will at least initially not cover as much area. Techniques such as store-and-forward systems will allow non-time sensitive data to be transmitted between two ground stations using one satellite, while satellite-to-satellite communications may shorten the time required to relay data..

Managing these situations will become a challenge for Network Operations Centers using satellite assets. In order to provide the best service and to enforce priorities, NOCs will desire to use common off the shelf (COTS) software such as Solarwinds and Satellite Tool Kit for satellite link integration.

The scope of this project will be to evaluate methods used to manage established low-earth orbit networks, and how these methods may be applied to the above scenarios. Actual TacSat availability is extremely limited by availability and production schedules, thus amateur radio satellites will be used as experimentation platforms to test voice and data networks feasibility. Immediate emphasis will be to manage RS-232 connections between the host computer and the radio terminal node controllers (TNCs). SNMP will

be investigated as a delivery vehicle, as well as the possible creation of proprietary protocols compatible with Automated Position Reporting System (APRS).

The thesis will also explore implementing working satellite connections, integrated with the TNT experiments. These connections may attempt to use unmanned aerial vehicles as an intermediary node to relay data to amateur/student satellites and ultimately to a ground station. This will be as time and funding permits.

II. PROBLEM ANALYSIS

Most communication satellites used by the government and commercial sectors have a geostationary orbit. While a geostationary orbit provides continuous coverage and ease of antenna alignment, it also requires higher power from the transmitter and higher antenna gain to make the 35,780 km trip.[20] The power and antenna directivity requirements may be a minimal challenge to a fixed station, but they eliminate the possibility of small hand-held devices to take advantage of the geostationary satellite's service.

LEO satellites however are much closer to the Earth's surface, and make it possible for hand-held devices to access satellite services. Iridium LLC and Globalstar have proven this capability through their collection of LEO satellite phones and modems, allowing an end user to have near cellular-phone quality of service for an initial investment of less than $1000 and $1 per minute.[21] Several amateur radio operators have communicated to each other through FM repeaters and AX.25 digital repeaters on board the International Space Station and OSCAR satellites with only 5 watt handheld radios which cost less than $350.[22]

Low Earth Orbiting Satellites have their own challenges, however. Overhead times of LEO satellites are measured in minutes, providing the challenge of tracking the satellite to know when access is available. Since this is completely non-feasible to commercial service providers, they must launch constellations of dozens of satellites to ensure the continuous coverage that a geostationary satellite would provide. To an amateur radio operator, this requires brief and precise communications to ensure that his/her message is sent, the acknowledgement and answer is received, and the satellite can still handle other communications.

20 Wiley J. Larson, Understanding Space: An Introduction to Astronautics, 2nd ed, (New York: McGraw-Hill, 2000), 164.

21 "Airtime Pricing" [web page] (cited 01 DEC 05); available from World Wide Web @ http://www.globalstarusa.com/en/airtime/voicepricing

22 Larry D. Wolfgang and Joel P. Kleinman, Now You're Talking: All You Need To Get Your First Ham Radio License, 4th ed, (Newington: ARRL 2000), 3-9.

A. LOW EARTH ORBITING SATELLITE NETWORK MANAGEMENT CHALLENGES

Networks using Low Earth Orbiting satellites face many challenges due to the nature of the orbit. Doppler Effects cause ISO Layer 1 (Physical (PHY)) characteristics to be in a near constant change, which is more prevalent with the higher UHF frequencies most hand held devices use. Additionally, networks using LEO satellite constellations must also deal with satellite hand-offs and satellite-to-satellite communications. Network users not having the advantage of constellations must time their transmissions in order to effectively communicate yet preserve availability for other users.

Federal Standard 1037C defines Doppler Effect as, "The change in the observed frequency (or wavelength) of a wave, caused by a time rate of change in the effective path between the source and the point of observation."[23] In LEO satellite communications, this causes a frequency mismatch between the ground transceivers and the satellite transceiver. Since ground transceivers are spread out in undetermined locations, a LEO satellite's transceiver cannot compensate for its own motion. Frequency adjustment is left to the ground stations to determine. The equation:

$$f' = f_0\left(\frac{1}{1+\frac{v}{c_0}}\right)$$

Figure 1. Doppler Shift Equation (from Doppler Shift)

where v is radial velocity in reference to the ground station, describes the change in frequency as the satellite passes by. For small f_0, the apparent change in frequency is less noticeable and can fall within tolerances of the receiver. The Iridium phone for example must compensate for as much as 70 kHz of Doppler shift and 20 kHz/min Doppler rates

[23] Telecommunications: Glossary of Telecommunications Terms, Federal Standard 1037C, (GSA: 1996), D-28.

through a typical pass.[24] Amateur radio operators communicating through the International Space Station's (ISS) cross band repeater must deal with maximum Doppler shifts of 3 kHz at 145.800 MHz and 9 KHz at 437.800 MHz.[25] In the case of a FM voice conversation through the ISS repeater, the voices will be slightly out of pitch and muffled when not accounting for the Doppler shift. However, frequency disparities at ISO Layer 1 cause potential corruption of data, especially at faster throughputs. While this challenge is fairly ease to overcome, doing so requires precise timing, knowledge of the ground station's position, and knowledge of the target satellite's orbit. Timing can be set over the network by a time server, determined by Global Positioning System (GPS) transmissions, or even by HF time servers such as WWV and WWVH. Updated Keplerian elements can be sent over the network, or the receiver can be intelligent enough to sense any signal from the satellite and determine its frequency. Position can be determined by GPS, the target satellite network, or manually entered.

The periodic orbit that causes Doppler Effect also causes a network to consider periodic and non-constant coverage by the satellite. In a constellation system, a transition system is required for the common case of the ground station changing satellites. Such transitions are similar in nature to cellular phone network hand-offs. Just like Doppler Effect, both satellite and ground stations systems in established network systems have discovered solutions to the transition problem. However, when using software such as Solarwinds for network discovery, the software must be prepared for a constantly changing network with satellite nodes coming and leaving every few minutes.

Network operations using isolated LEO satellites may not have to handle transition, but must be able to withstand short periods of activity followed by longer periods of inactivity. While the satellite is not overhead, buffers must be monitored to ensure that an overflow condition does not exist. Should the satellite possess a store-and-forward capability, care should be given to monitor the satellite's buffer before transmitting additional data to the buffer. As an example, University of Surrey's

[24] John Braegan, "SATGEN408: Iridium Mobile Phones" [Amateur Radio Packet Radio Bulletin, 17 January 1997] (cited 01 DEC 05); available from World Wide Web @ http://www.amsat.org/amsat/ftp/articles/satgen/sgen408.txt

[25] Charlie Sufana, "Doppler Correction Chart" [web page] (29 July 2005 [cited 01 DEC 05]); available from World Wide Web @ http://www.amsat.orgamsat/ariss/news/ISS_frequencies_and_Doppler_correction.rtf

UoSAT-OSCAR-14 experienced several instances of filled buffers, forcing satellite controllers to shorten the storage life of each message and eventually switch operations over to UoSAT-OSCAR-22.[26] While having to opportunity to swap missions with another satellite was advantageous, this highlights the need for a management process to prevent future satellites from experiencing similar problems.

B. CURRENT LOW EARTH ORBITING SATELLITE MANAGEMENT PROCESSES

With the variety of transmission protocols and data protocols used in LEO Satellite communications, no one management protocol can cover all communications. Some satellites may offer IP routing and have a SNMP agent available to incorporate management data into an overall network management system. Commercial systems may have proprietary protocols for their own usage, either leaving customers to derive data from other sources or providing a simple set of variables that customers may use while troubleshooting their ground stations. Amateur radio applications may require log analysis and downlink monitoring to determine satellite link efficiency.

1. PPP Management Information Base (MIB)

In some cases, such as the TNT experiment team's use of Iridium satellites, satellites are simply providing a circuit-like connection through which data can travel. Through these circuit-like connections, many satellite service packages use the Point-to-Point Protocol (PPP) family of protocols as the data transport medium.[27] The Object identifier (OID) for viewing the PPP Family of Management Information Bases (MIBs) is 1.3.6.1.2.1.10.23.[28] This MIB in a data only system will provide the status of the link from the object under monitoring and the other end of the PPP connection. When using dial-up services in Iridium, the other end of the PPP connection will be the destination computer called; in TNT's case it is the Naval Postgraduate School Remote Access Service (RAS) Server.

[26] John A. Magliacane, "Spotlight On: UoSAT-OSCAR-22", The AMSAT Journal, vol. 15, no. 3, (1992 [cited 07 DEC 05]). available from World Wide Web @ http://www.amsat.org/amsat/sats/n7hpr/uo22_hd2.html

[27] Swee Keong Joo and Tat Chee Wan, "Quality of Service (QoS) Issues over Satellite Links", Proceedings APAN 2000 Conference, Beijing, P. R. China, (APAN, 2000), 2.

[28] J. Reynolds and J. Pastel, RFC 1700 – Assigned Numbers, (Marina Del Rey: ISI, 1994)

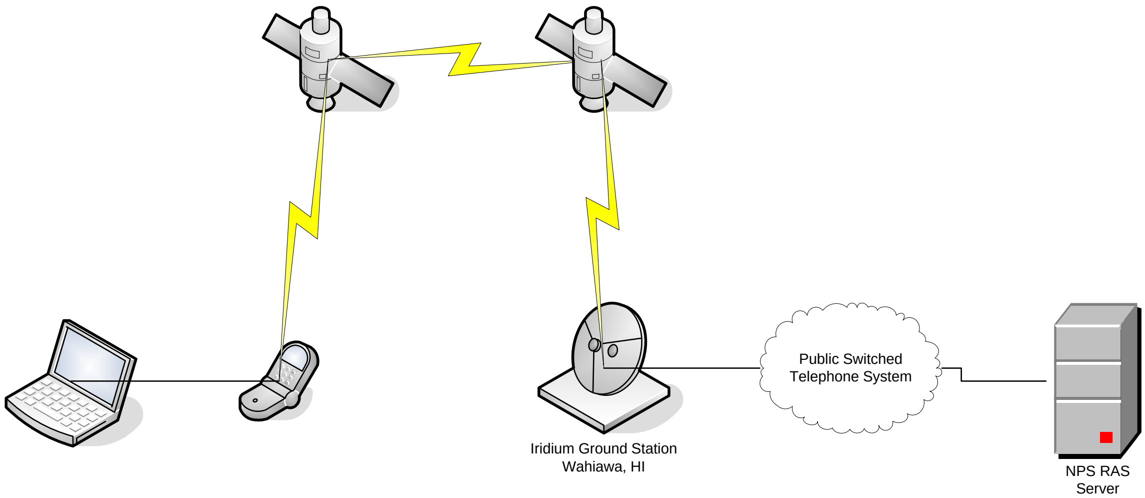

Figure 2. PPP Transmission Path for Typical NPS TNT Iridium Usage

2. SMIB

Iridium and Globalstar have both proved various methods of deploying a network via a constellation of LEO satellites. Currently, various organizations are researching taking the Iridium network model and applying the idea to a satellite ATM system. One proposal for managing the ATM network (which will be covered later in the chapter) is through the Satellite Management Information Base (SMIB).

SMIB currently resides in the experimental portion of the MIB-II data set. Figure 3 below describes its location in the MIB tree.

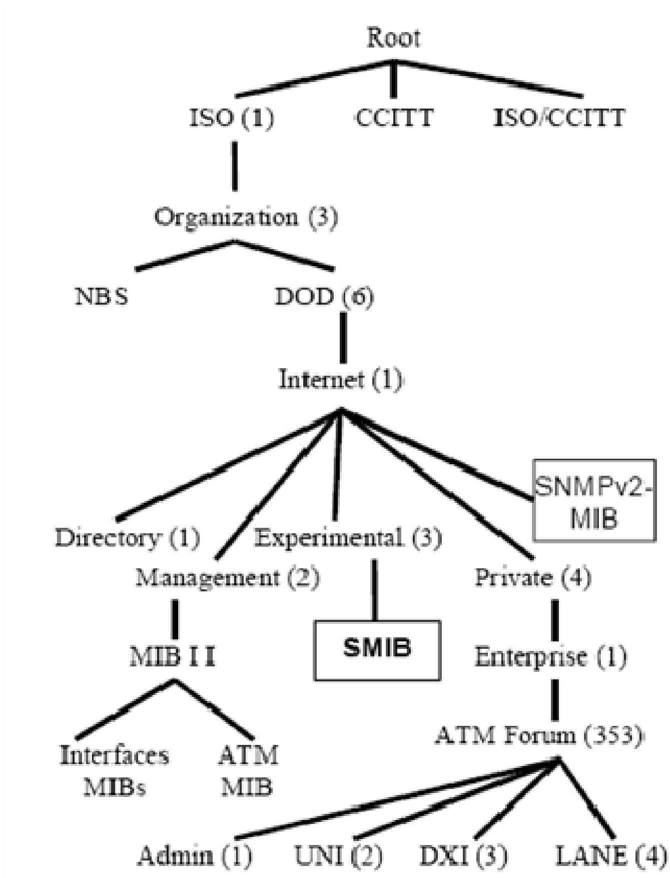

Figure 3. Illustrating the MIB Management Tree (from "Network Management in ATM LEO Satellite Networks")

SMIB will be controlled through the SMNP v.2 protocol, which will travel through the ATM Application Layer 5 (AAL5), and will provide services for monitoring hardware and ATM variables.[29] Figure 4 below shows SMIB's position in the ATM protocol stack.

29 Petia Todorova, "Network Management in ATM LEO Satellite Networks", Proceedings of the 35th Hawaii International Conference on System Sciences – 2002, (IEEE, 2002), 5-6.

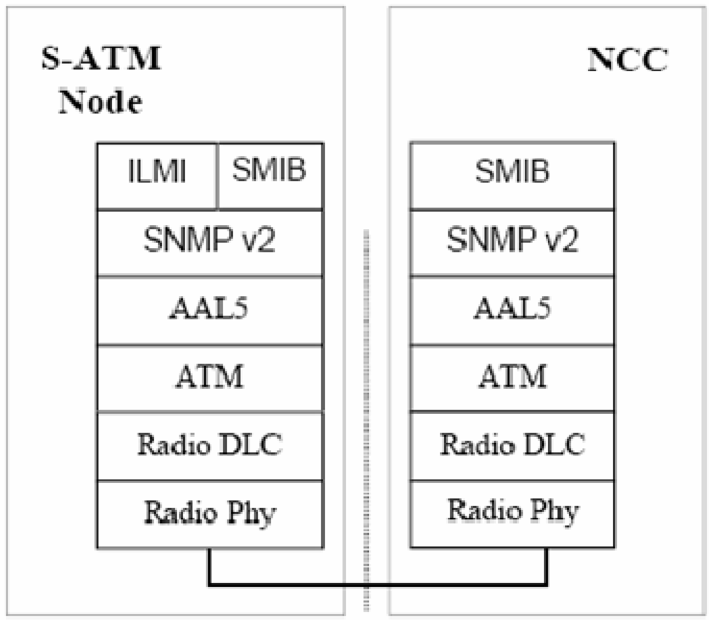

Figure 4. Illustrating the Network Management Protocol Stack (from "Network Management in ATM LEO Satellite Networks")

Specialized channels on each satellite will maintain communications between itself, the two adjacent satellites in the same orbit, and the two adjacent satellites in neighboring orbits.[30] This interconnection will allow the Network Control Center (NCC) or Network Operations Center (NOC) to conduct management functions with any satellite in the constellation.

3. Signal Monitoring

In many amateur radio satellite operations, those wishing to collect network management information must use a much more manual approach to determine network parameters. The AX.25 protocol, commonly used as the Layer 2 protocol for amateur satellite data transmissions and amateur radio packet transmissions, is often used by hobbyists with little to no desire to maintain network statistics on their systems. In a connected mode environment, radio amateurs judge network performance by how frequently packet transmissions are retransmitted and whether the application or user on the other end returns an expected response to the communication. Fault management

[30] Petia Todorova, "Network Management in ATM LEO Satellite Networks", Proceedings of the 35th Hawaii International Conference on System Sciences – 2002, (IEEE, 2002), 3.

generally consists of increasing power, verifying transmit and receive frequencies, verifying antenna azimuth and elevation, and in more extreme cases antenna troubleshooting.

Amateur satellites not operating bulletin board services or store-and-forward networks frequently operate in a connectionless mode. In this mode, an amateur radio operator can determine packet loss and packet corruption by comparing what is sent from the ground station, and manually comparing it with what the satellite digitally repeats (digipeats) on the downlink. Most packet radio software applications can also record a log of packets transmitted and received, which can be analyzed at a later time and compared with other stations' logs. This method was the primary tool for the TNT Satellite Group to analyze experiment results in its APRS experiments.

C. LEO COMMERCIAL TELEPHONY AND DATA NETWORKS

Maritime travel, disaster communications, and remote area operations all have justified the existence of LEO satellite commercial networks. These networks consist of constellations of satellites that relay voice and data traffic to a gateway station. These services provide standard telephone service as well as low data rate PPP connections to users, using cellular phone style equipment that is slightly bulkier than terrestrial cellular phones. Information concerning internal network management systems appears to be tightly controlled by the companies.

1. Iridium

The Iridium network system consists of a constellation of 66 operational satellites, at an altitude of 485 miles above Earth.[31] The satellites operate in a mesh network, each one communicating with 2 co-orbiting and 2 adjacent orbiting satellites.[32] Through the inter-satellite links, signals travel from the subscriber to one of three terrestrial network gateways.[33] The U.S. Government maintains a gateway in Hawaii, and Iridium, LLC maintains gateways in Arizona and Fucino, Italy.[34] Subscribers are assigned one of these

[31] Iridium Satellite Data Services White Paper, v 1.0, 2 June 2003, 3.

[32] Ibid.

[33] Ibid.

[34] "Quick Reference – Gateway" [web page] (cited 09 DEC 05); available from World Wide Web @ http://www.nalresearch.com/QuickRef_Gateway.html

gateways as the connection point for terrestrial service.[35] Data rates of up to 2400 bps are available for dial-in connections to subscribers' Internet service providers, or up to 10 kbps if subscribers use Iridium's Direct Internet Data Service.[36]

2. Globalstar

The Globalstar network system consists of a constellation of 40 operational satellites, at an altitude of 876 miles above Earth.[37] Satellites in the constellation operate independently through a "'bent pipe' architecture" and combine a subscriber's signal from multiple satellite feeds at the gateway.[38] Globalstar operates 24 gateway stations throughout the Americas, Europe, Asia, and Australia.[39] Data rates of 9.6 kbps are available for subscribers to access to both Globalstar's Internet service and private networks.[40]

3. Comparisons

Each network has its strengths and weaknesses. An independent company found that Globalstar connections tend to be more successful than Iridium connections.[41] Differences in quality can be attributed to multiple hops through the Iridium satellite network versus a single hop through a satellite, increasing both the scope of potential errors and the latency. For the subscriber, Iridium has a single point of failure at the subscriber's assigned gateway station. For Globalstar, however, the subscriber must be within a single-hop range of a gateway in order to have service. In large disasters, the nearby Globalstar gateway may be damaged, removing coverage for the surrounding area. Since satellites are meshed in Iridium, coverage for a disaster affected area will be

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35"Quick Reference – Gateway" [web page] (cited 09 DEC 05); available from World Wide Web @ http://www.nalresearch.com/QuickRef_Gateway.html

36 "Using Iridium – Services" [web page] (cited 09 DEC 05); available from World Wide Web @ http://www.iridium.com/service/iri_service-detail.asp?serviceid=2

37 "How Globalstar Works" [web page] (cited 09 DEC 05); available from World Wide Web @ http://www.globalstar.com/en/works/constellation/

38 Ibid.

39 "Coverage" [web page] (cited 09 DEC 05); available from World Wide Web @ http://www.globalstar.com/en/content.php?cid=300

40 "Data Communications" [web page] (cited 09 DEC 05); available from World Wide Web @ http://www.globalstarusa.com/en/data/dataprod/gsp1600.php

41 "Satellite Telephone Quality of Service Comparison: Iridium vs. Globalstar" [web page] (cited 09 DEC 05); available from World Wide Web @ http://common.globalstar.com/docs/fs_study.pdf

less affected unless the disaster happens to coincide with one of the three gateways. Furthermore, Iridium has near global coverage, while Globalstar only has coverage in the vicinities of their gateways.

D. SATELLITE NETWORK PROTOCOLS

While there are many protocols that are used in satellite communications, some of the more common protocols in use are listed below.

1. AX.25

The AX.25 protocol is the most widely used Layer 1 / Layer 2 protocol used in amateur radio. It is specially designed to operate among peers, rather than the master and slave relationship, removing the need to configure modes for each connection.[42] Within the protocol, three separate frame types exist: the Information Frame, the Supervisory Frame, and Unnumbered Frame.[43] These frames allow for communication in both a connection-oriented and connectionless communications. While modern computers are capable of digital signal processing through the sound card, terminal node controllers (TNC) are the traditional way of using AX.25, working much like a modem between the computer and radio. Figure 5 below displays the layout of the protocol:

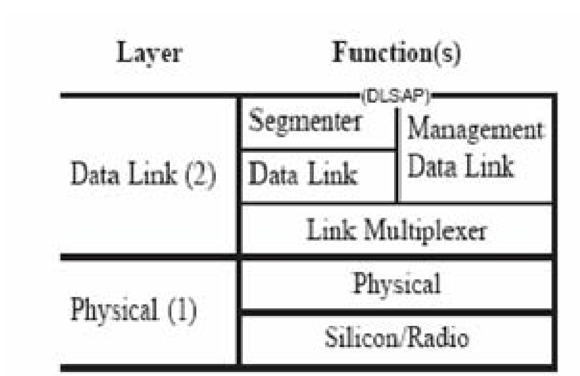

Figure 5. ISO Layer Mapping of AX.25 (from AX.25 Link Access Protocol for Amateur Packet Radio)

[42] William A Beech, Douglas E. Nielsen, and Jack Taylor, AX.25 Link Access Protocol for Amateur Packet Radio, (Tucson Amateur Packet Radio Corporation, 1997), 1.

[43] Ibid, 6.

Layer 1 consists of the RF connection and the TNCs and radios on either end. The Link multiplexer allows multiple sessions to use the same physical layer.[44] The Management Data Link State Machine handles the parameters of the AX.25 connection.[45] The Data Link State Machine controls the connection establishment and breakdown, as well as passing information.[46] The Segmenter accepts information from higher layers, and segments the information to fit within the frame is needed.[47]

Addresses in AX.25 are based on call signs, with a four bit SSID number to identify multiple stations under the same call sign.[48]

Figure 6 displays the construction of an AX.25 frame:

Flag	Address	Control	PID	Info	FCS	Flag
01111110	112/224 Bits	8/16 Bits	8 Bits	N*8 Bits	16 Bits	01111110

Figure 6. Information Frame Construction (from AX.25 Link Access Protocol for Amateur Packet Radio)

The Flag octet signifies the beginning and the end of the frame. The Address field signifies the origin and destination addresses, along with any digipeaters to traverse en route. The Control field identifies the frame type, and controls several Layer 2 properties. PID identifies what Layer 3 protocol is any is carried in the Info field, and is only present in an Information frame, or an Unnumbered Information frame. The Frame Check Sequence field verifies the frame integrity.[49]

AX.25 is the common data protocol for amateur radio satellites, and is the backbone for VHF and UHF data communications in amateur radio. It is also the protocol enabling the Automated Packet Reporting System.

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[44] William A Beech, Douglas E. Nielsen, and Jack Taylor, AX.25 Link Access Protocol for Amateur Packet Radio, (Tucson Amateur Packet Radio Corporation, 1997), 3

[45] Ibid, 5.

[46] Ibid, 4.

[47] Ibid.

[48] Ibid, 9.

[49] Ibid, 6-8.

2. Automated Packet Reporting System (APRS)

In 1992, Mr. Robert Bruninga of the U.S. Naval Academy Satellite Laboratory introduced APRS to the Tucson Amateur Radio Corporation/Amateur Radio Relay League's Digital Communications Conference.[50] Since then, APRS has become one of the most popular data modes for VHF and UHF amateur communications. APRS provides users the opportunity to report their position to a network, and receive position data from other stations. Many APRS programs will take this data and plot positions on a map. Users can also send messages over the network. Internet connectivity offers users a world view of APRS activity, and gives users the flexibility to send and receive short e-mails from the Internet.

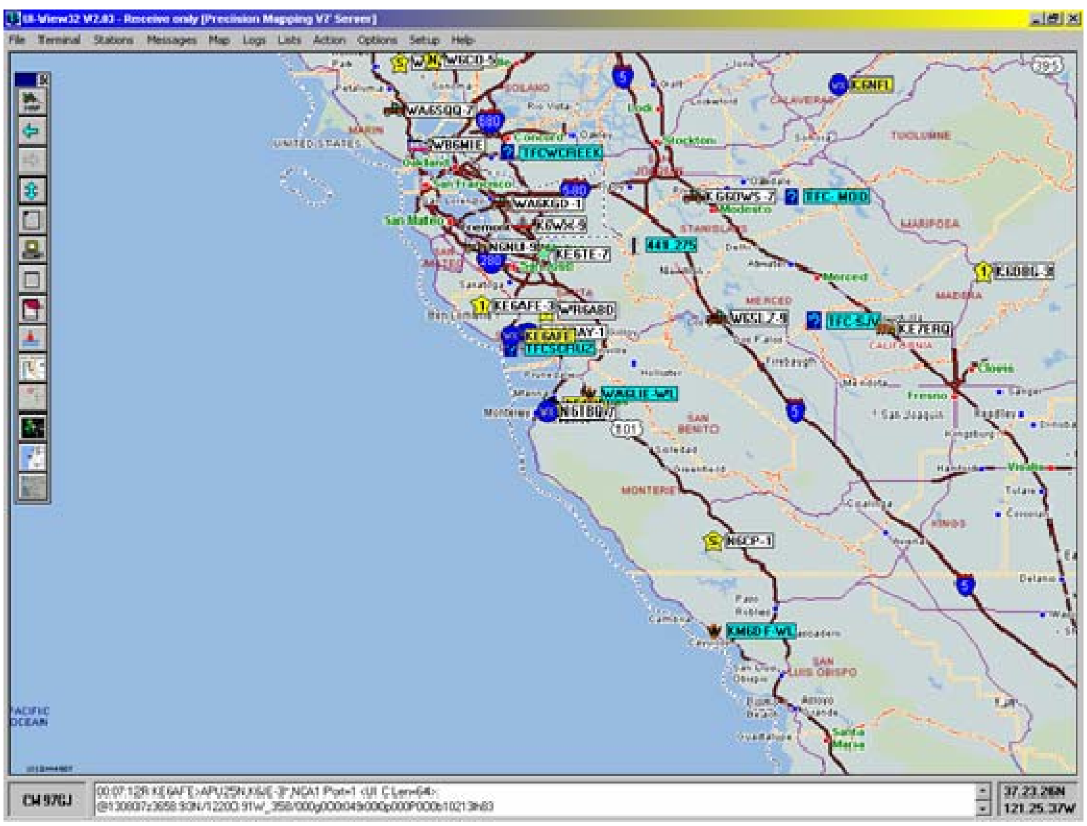

Figure 7. APRS View of Central California via the Terrestrial Network

50 Ian Wade, APRS Protocol Reference, v1.0.1, (Tucson: TAPR, 2000), 7.

APRS can be sent over a variety of systems, but for amateur radio it uses AX.25's Unnumbered Information (UI) frame, and travels within the information field.[51] APRS uses AX.25's destination address field to place a generic destination, map symbol data, a message type, software identification, and compressed position information.[52] Figure 8 displays the use of the information field:

	Generic APRS Information Field			
	Data Type ID	APRS Data	APRS Data Extension	Comment
Bytes:	1	n	7	n

Figure 8. APRS Data in AX.25 Information Field (from APRS Protocol Reference)

The Data Type ID field tells the software how to handle the rest of the data. The APRS Data field can report station position, objects, weather data, messages, queries, and more. The Data Extension field is optional, based on the data type. The Comment field provides for an ASCII text comment to be added to the data.

Because APRS is a connectionless, datagram protocol providing near-real time data, it is an excellent candidate for amateur satellites. Currently, PCSAT2 on board the International Space Station (ISS) is mission-capable for APRS relay, depending on sunlight exposure for battery charging, and PCSAT is capable only in times of peak sunlight. A digipeater on board ISS is capable of transmitting both APRS and AX.25 UI frames, and not as subject to solar conditions..

3. PPP

The Point-to-Point Protocol is a Layer 2 protocol used to establish connections between two peers, and allows multiple Layer 3 protocols to be transmitted within the connection. It consists of a Link Control Protocol (LCP) to establish and break down

[51] Ian Wade, APRS Protocol Reference, v1.0.1, (Tucson: TAPR, 2000), 12.

[52] Ibid, 13.

connections, and several Network Control Protocols (NCP) in order to configure the connection to accept the protocol's encapsulated Layer 3 packet.[53] Figure 9 below displays a typical PPP frame:

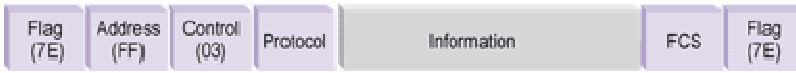

Figure 9. PPP Frame *(from* Protocol Analysis: Unit 2- LAN and WAN Protocols: Lesson 5 – SLIP and PPP)

Like the AX.25 frame, the Flag fields allows for synchronization.[54] The Address Field is always set to "All Users".[55] The Control field is always set to 00000011 for a PPP frame.[56] The Protocol Field identifies what type of PPP frame it is, or what Layer 3 protocol is encapsulated.[57] The FCS frame provides a check sum.[58]

Since setup and break-down of PPP connections is easier than other methods for the common user, it is the popular method of establishing dial-up connections.[59] CENETIX frequently uses PPP connections in conjunction with Globalstar and Iridium Satellite modems in order to establish low throughput connections with the NPS and CENETIX networks.

4. ATM

Another Layer 2 protocol, Asynchronous Transfer Mode (ATM) is a connection-oriented suite of protocols used to transfer digital voice and data.[60] This complex suite consists of a basic ATM layer which provides the foundation for a series of ATM Adaptation Layers (AAL).[61] Each AAL is tailored for a specific type of payload.[62] In

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53 W. Simpson, The Point-To-Point Protocol, RFC 1661, July 1994.

54 W. Simpson, PPP in HDLC-Like Framing, RFC 1662, July 1994

55 Ibid.

56 Ibid.

57 W. Simpson, The Point-To-Point Protocol, RFC 1661, July 1994

58 W. Simpson, PPP in HDLC-Like Framing, RFC 1662, July 1994

59 Tamara Dean, Network+ Guide to Networks, 2nd ed., (Boston: Course Tehnology, 2002), 339.

60 "ATM: Asynchronous Transfer Mode Protocol" [web page] (cited 18 DEC 05); available from World Wide Web @ http://www.javvin.com/protocolATM.html

61 Ibid.

the case of high-speed data networking, AAL5 is the most used layer for transport.[63] Figure 10 shows a typical AAL5 cell layout.

0-48 Bytes	**0-47**	**1**	**1**	**2**	**4 Bytes**
PDU payload	PAD	UU	CPI	LI	CRC-32

Figure 10. AAL5 Convergence Sub-layer Protocol Data Unit (from AAL: ATM Adaptation Layer (AAL0, AAL2, AAL3/4, AAL5))

The padding ensures that the cell length is maintained even with differing payload lengths.[64] The UU is a User-to-User indication, to allow for compatibility with higher protocols.[65] The CPI (Common Part Interface) aligns the trailer (UU, LI, CRC-32) to 64 bits, and may have future uses. The LI (length indicator) reports the length of the payload. The CRC-32 provides for a cell check sum.[66]

Those looking into a data LEO satellite network are choosing ATM because of the availability of throughput on demand, combined with a guarantee of quality of service. It also provides the capability of intelligent switching over the satellite network, rather than a bent-pipe situation.[67]

62 "AAL: ATM Adaptation Layer (AAL0, AAL2, AAL3/4, AAL5)" [web page] (cited 18 DEC 05); available from World Wide Web @ http://www.javvin.com/protocolAAL.html

63 Ibid.

64 Ibid.

65 Ibid.

66 G. Gross et al, PPP over AAL5, RFC 2364, July 1998.

67 Petia Todorova, 1.

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III. REQUIREMENTS DEFINITION AND LOGICAL DESIGN

The Center of Network Innovation and Experimentation's (CENETIX) Tactical Network Topology (TNT) experiment series began using Iridium and Globalstar assets prior to this thesis, with the emphasis being solely on results. While the desire existed to monitor the satellite links, nothing was in place to do so.

A. SPECIFICATIONS OF NEEDED SATELLITE USAGE IN TNT

As the CENETIX team continues to make new partnerships globally, the need for satellite access continues to develop. The CENETIX team desires to use terrestrial networks whenever possible due to cost and availability of link monitoring, but satellite access is beginning to become increasingly needed as terrestrial solutions become more difficult to develop. Additionally, miniaturized nodes used in the TNT experiments, that are isolated from other network resources, depend on satellites to relay their data back to the network operations center for fusion. Both of these needs will continue to grow in the foreseeable future.

1. Network Expansion

The globalization of the CENETIX experiments requires available links to share data between the experiment location and the established TNT private network. Often times, terrestrial connectivity will be impossible because of either geographic location or network policies of participating players. These needs are often best addressed through using geostationary satellites, as a fixed site can be used to uplink with the satellite.

a. iDirect

The iDirect Private Hub system is one product that provides geostationary satellite connectivity between two separate points, without having to transport data through the Internet. This system is scalable for throughputs of 4.2 Mbps uplink and 18 Mbps downlink.[68] Should this system be employed, one hub would be at the experiment site, and the other would be set up at Naval Postgraduate School for direct connection with the TNT network. As iDirect only sells the equipment, CENETIX would have to find a compatible satellite internet service provider.

68 "The iDirect Private Hub" [web page] (cited 10 JAN 06); available from World Wide Web @ http://www.idirect.com.mx/iDirect_Private_Hub_Satellite_Router.pdf

b. DIRECWAY

DIRECWAY provides Internet satellite connectivity to predominantly fixed station users. Mobile use of this service is available through other providers, such as Ground Control used by NPS for Nemesis. Service of 2 Mbps downlink and 512 Kbps uplink is possible with this system.[69] Difficulties in coordinating a terrestrial connection in the Alameda Island experiment gave the newly installed system in Nemesis its first operational test. VPN concentrators are used to provide access to the NPS network, from which experimenters obtained access to the TNT network.

2. Miniaturized Node and Mobile Access

Nodes such as deployable field sensors and human deployable gear require connectivity that does not require antenna positioning and can be conducted using low power out of inefficient antennas. Mobile nodes may enjoy the additional space for high power equipment and antenna positioning devices, but still face an antenna tracking problem when traveling at higher speeds. While geostationary satellites are being developed that can accommodate these needs, currently low-earth orbiting satellite best fulfill these nodes' requirements.

a. Iridium

As discussed in Chapter II, Iridium offers low throughput solutions for cellular phone-sized solutions. This solution is currently implemented in the TNT experiments in order to relay sensor video and other data to the network operating centers. As Iridium is global, this is one solution to isolated sensors which may be deployed without a large infrastructure to support the node.

b. Amateur LEO Satellites

These satellites offer a glimpse of what could be done. Since most of these satellites operate independently of one another and have differing missions, currently no system is available to easily take advantage of these satellites to fulfill network requirements. So far, the APRS protocol has the most potential to become a standard in amateur satellites, but currently there are only 2 operational satellites with APRS. For the purposes of TNT experiments, the authors recommend continuing to use PCSAT-2 on board the International Space Station for experiments, as it is easiest

[69] "Mobile Bandwidth" " [web page] (cited 10 JAN 06); available from World Wide Web @ http://www.groundcontrol.com/mobile_bandwidth.htm

maintained on the manned station, and it is owned and controlled by the U.S. Naval Academy. AO-51 is currently the other APRS satellite available, although it is in testing.[70]

B. SYSTEM MODELS OF FIXED AND MOBILE GROUND STATIONS

The models below detail both working and future stations used in experimentation.

1. Naval Postgraduate School "Groundstation"

Figure 11 displays the high level schematic of the NPS "Groundstation":

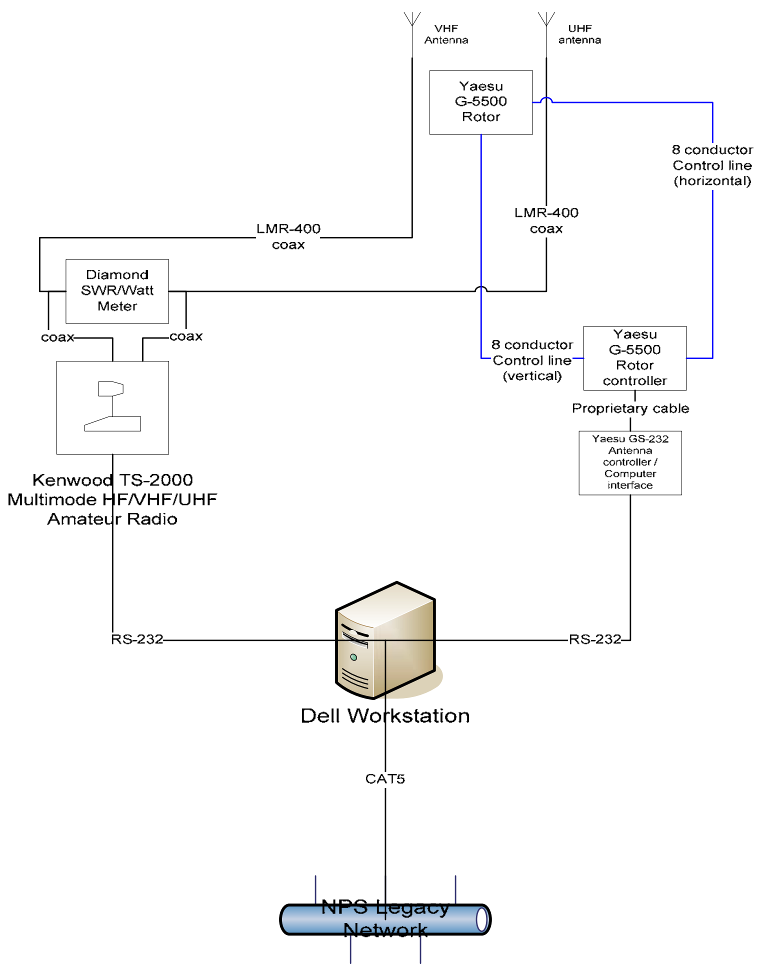

Figure 11. NPS "Groundstation"

70 Robert Bruninga, "Re: [aprssig] Fwd: [amsat-bb] AO51 Digipeater Trial Test" [electronic bulletin board] (20 DEC 05 [cited 10 JAN 06]); available from listserv @ aprssig@lists.tapr.org

The workstation consists of a Dell Optiplex 870 Workstation, with dual screen monitors and three RS-232 ports. Critical experiment software installed includes:

- Windows XP Professional operating system
- UI-View32 version 2.03 (For APRS)
- Winpack version 6.8 (For Non-APRS AX.25 communication)
- AGI Satellite Tool Kit (for modeling)
- Nova for Windows version 2.2b (For satellite tracking and rotor control)
- Precision Mapping version 7.0 (Map background for UI-View32)
- Kenwood ARCP-2000 (For computerized radio control)

The Kenwood TS-2000X Transceiver is a HF/VHF/UHF multimode radio, capable of performing most amateur radio operations. The functionality of this radio allows flexibility for further experiments. Critical to this thesis' experiments is the integrated Terminal Node Controller (TNC), which serves as an AX.25 modem interface for the radio. Control of the radio can be performed either at the panel or through use of the ARCP-2000 software; however, software control and TNC operations cannot occur simultaneously. One RS-232 connection provides both functions. Separate coaxial cables provide the VHF and UHF feeds. The accompanying Diamond SWR/Power meter provides power output and SWR information for any of the Kenwood's frequency bands.

Rotor control for the antennas is through a RS-232 connection to the Yaesu GS-232B computer interface box. This box translates ASCII commands sent from the attached computer to signals to be processed by the rotor control box. The Yaesu G-5500 rotor system consists of the rotor and the control box. A proprietary cable provides connection between the control box and the GS-232B. From the control box, two eight conductor controls lines connect the rotor. The control lines, one for vertical and one for horizontal, provide both movement control and power to the rotor, using seven of the eight conductors.

Figure 12. Groundstation Control Console

The antennas are M^2 circularly polarized Yagis. The VHF antenna is the 2MCP14, and the UHF is the 436CP30. Both are installed for right-hand circular polarization. The mast consists of a tripod mount, with an eight foot mast and a ten foot boom.

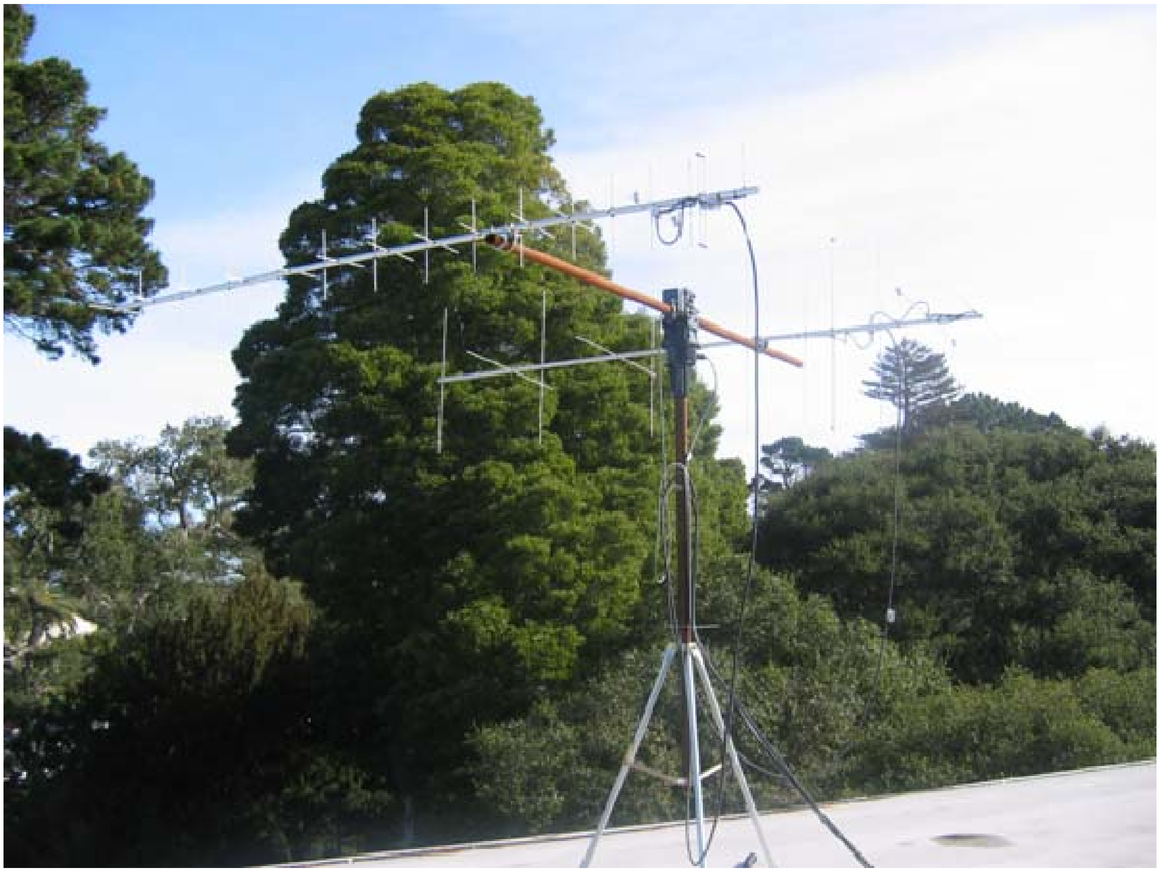

Figure 13. Groundstation Antennas

"Groundstation" has successfully made contacts with other earth stations through the International Space Station packet digipeater. Future endeavors for this station would be to install the additional coaxial cable and 1.2 GHz antenna, and to eventually find a solution for a HF antenna. Operation of this station requires the user to possess a Technician Class (General Class for HF) FCC Amateur Radio Operator License or higher. The call sign for this station is K6NPS, courtesy of the Huggermugger Club at NPS.

2. Nemesis Network Operations Center

Figure 14 displays the high-level schematic for Nemesis.

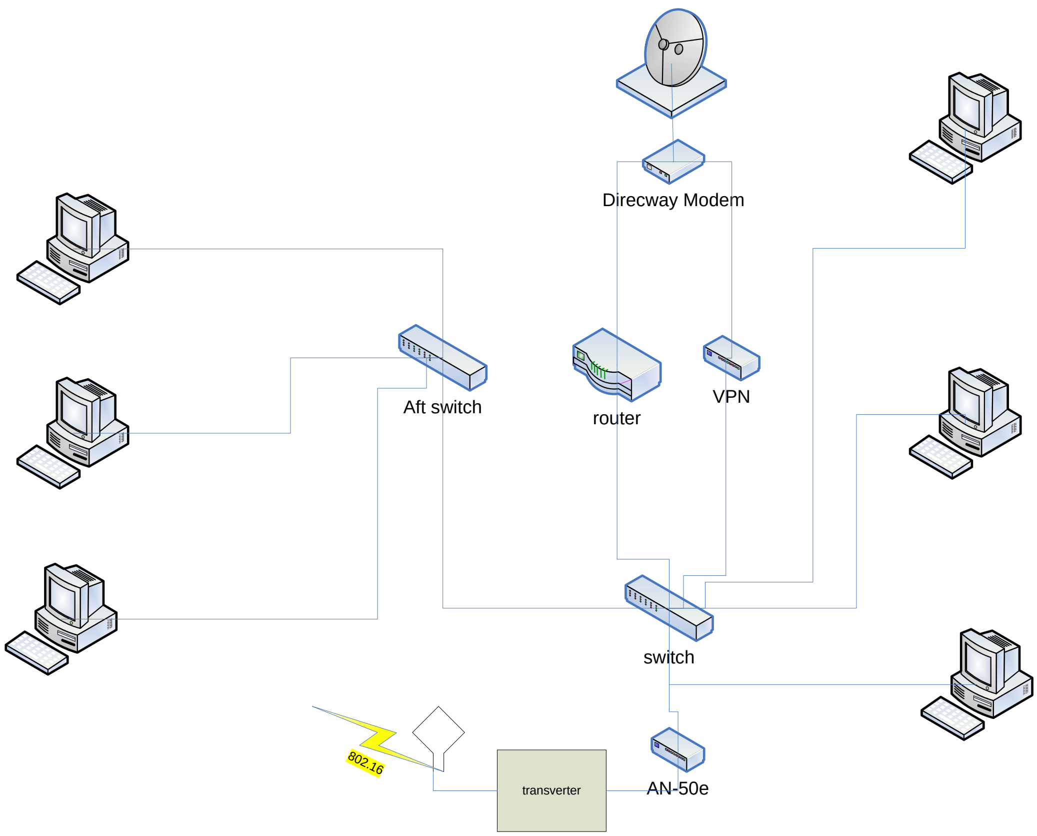

Figure 14. Nemesis Network Operating Center

The Nemesis Network Operation Center, developed and maintained by Major Oros and Michael Clement, is a converted recreational vehicle capable of deploying to a remote location and establishing satellite network connectivity nearly instantly. Through the use of Nemesis, CENETIX can extend the experiment test bed rapidly, and provide connectivity to remote units in the area.

Internet connectivity is established through the used of a DIRECWAY modem, connected to the satellite dish on the roof. Both a router and a VPN concentrator are connected to the modem, which provides separate routes for network traffic. The decision of which route occurs at the switch. The switch also serves three workstations,

an AN-50e bridge for IEEE 802.16 connectivity, and a second switch. The second switch connects three additional workstations to the network.

3. Mobile APRS and AX.25 Satellite Ground Station

Figure 15 describes a notional mobile satellite ground station, which can be installed in either Nemesis or the CENETIX Light Reconnaissance Vehicle. This is also the current configuration used in LT Richard Clement's private vehicle during experiments.

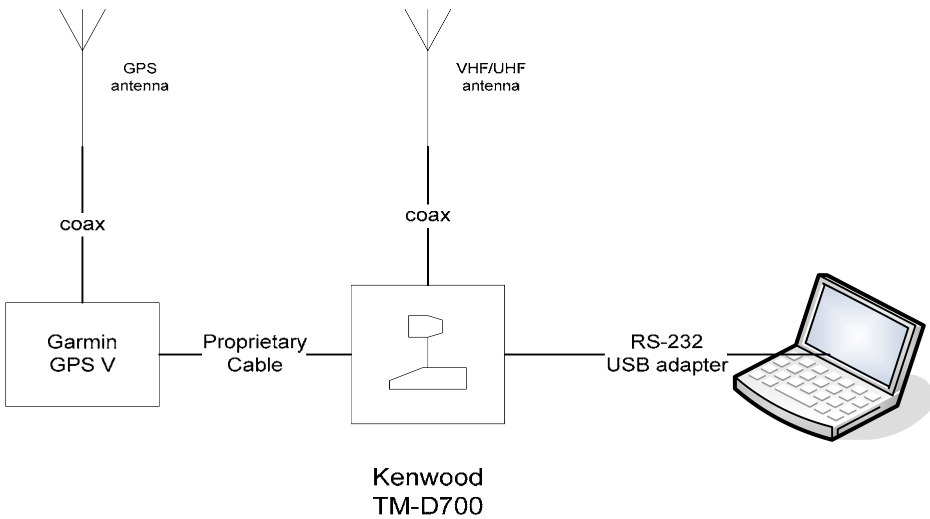

Figure 15. Mobile APRS/AX.25 Satellite Ground Station

The Kenwood TM-D700 is a VHF/UHF dual band FM transceiver, specifically designed for APRS. Like the TS-2000, it has an integrated TNC. In future experiments, the TM-D700 can be used to control and communicate remotely through the TS-2000X for HF. The TM-D700 can either operate as a stand-alone APRS station, or can operate as a nearly fully-functional AX.25 station with a laptop connected to its RS-232 port. Also connected to the radio is a GPS unit, in this case Garmin's GPS V.

The laptop used throughout the experiments had the following software loaded:

- Windows XP Professional operating system
- UI-View32 version 2.03 (For APRS)
- Nova for Windows version 2.2b (For satellite tracking)

- Precision Mapping version 7.0 (Map background for UI-View32)

The antenna for the system should be a low-gain dual band antenna, in order to reach the satellite above the horizon. In the experiments, the antenna used was a generic brand cellular look-alike dual band antenna, attached with a New Motorola (NMO) mount on the roof.

When installed, the call sign K6NPS-2 is reserved for its use. For the experiments, LT Clement's mobile call sign of AE6QE-7 was used. Again, a Technician's class FCC Amateur Radio License or higher is required in order to operate this station.

4. Iridium Sensor Station

Figure 16 describes a nominal Iridium sensor station.

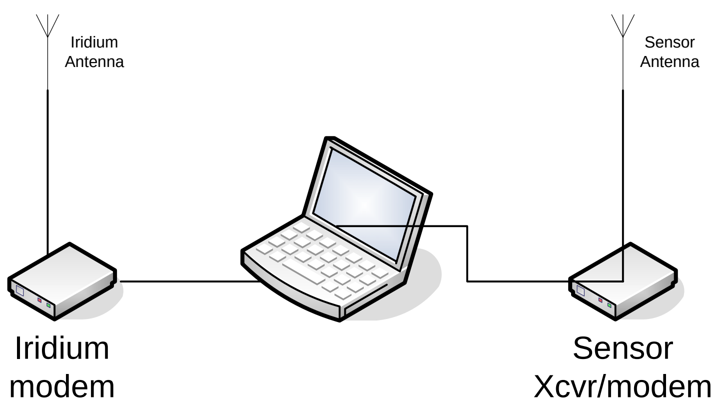

Figure 16. Iridium Sensor Station

Information from field sensors is sent to a collection point, and is received by the transceiver modem. Information is then processed inside a computer, and then sent to the Iridium modem for transmission. The modem could be a satellite telephone, a separate device, or potentially a PCMCIA card.

C. DATA FLOW AND NETWORK DIAGRAMS

The following diagrams display the data paths of both current and proposed satellite network systems.

1. APRS

Figure 17 displays the network diagram for an APRS Satellite operation.

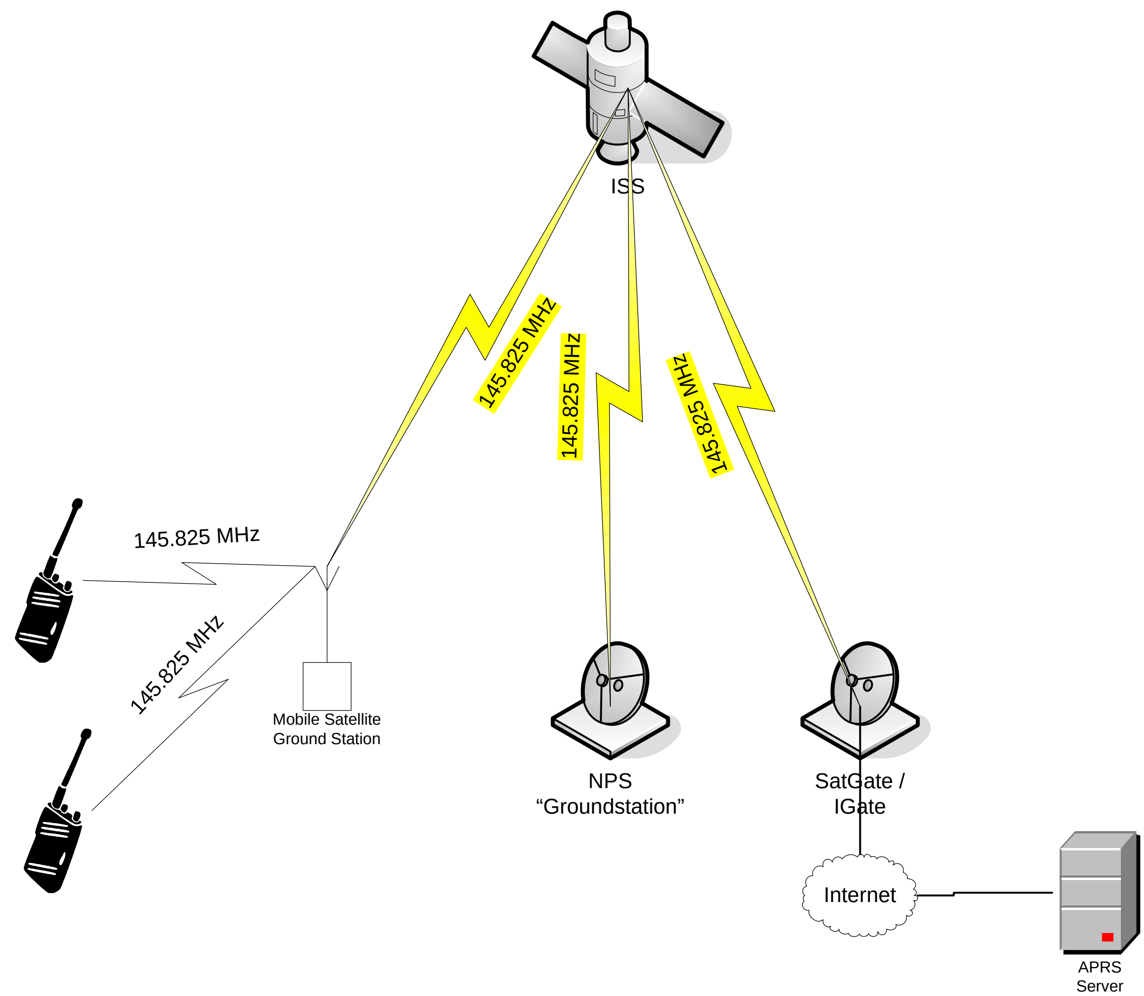

Figure 17. APRS Satellite Network

In this situation, all RF activity occurs on 145.825 MHz using 1200 bps Audio Frequency Shift Keying (AFSK). Field units would communicate either directly or through a mesh to a mobile satellite ground station, as described by Figure 3-3. With more available power, the mobile station would digipeat the field units. PCSAT-2 onboard ISS would digipeat the stronger signal of the mobile station, which could be received by NPS "Groundstation", and nearby Satellite Gateways with Internet Gateways. Data received by the Internet Gateway then travels through the Internet, and reaches an APRS server. From the APRS server, both client software and World Wide Web servers can access the position data along with any messages communicated. NPS "Groundstation" can also send messages to the field units, through PCSAT-2 and the mobile station.

While this network set up completes the mission requirement, greater flexibility is possible if the mobile station has the capacity to use two frequencies and two TNCs. Then, the mobile station can act more like a switch than a repeater, and the field units could occupy another frequency. Separate frequencies would ease network congestion and improve weak signal reception from the satellite to the mobile station. With an additional external TNC, the TM-D700 in Figure 3-3 is capable of accomplishing this task.

2. Iridium Network in TNT

Figure 18 illustrates the Iridium Network as used in TNT experiments.

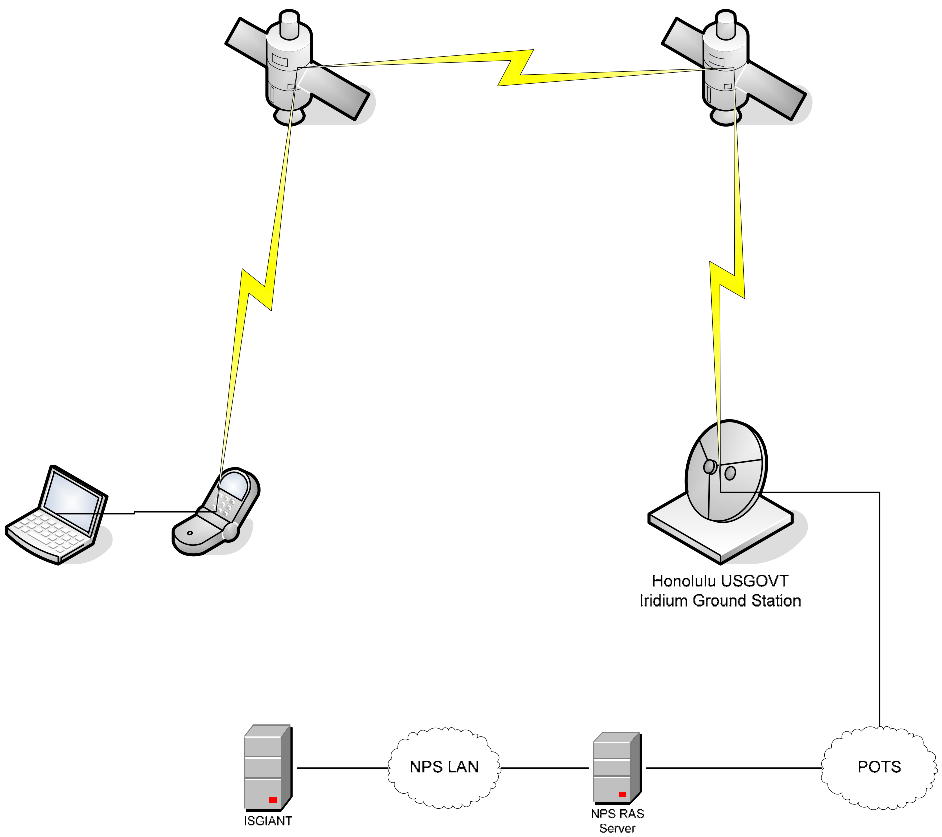

Figure 18. Iridium Network during TNT Experiments

The sensor control system communicates with an Iridium Satellite. A bounce to another satellite is required to span the distance to Honolulu, HI where the U.S. Government maintains a ground station for its subscribers (Civilian U.S. service would go through a ground station in Tempe, AZ). Then the signal is transferred to a telephone

line, which traverses the telephone network and terminates at the NPS RAS Server. The NPS RAS Server provides access to the NPS LAN, where the sensors' data is routed to ISGIANT Server.

3. Nemesis

Figure 19 illustrates the network path used by Nemesis when communicating with the NPS Network.

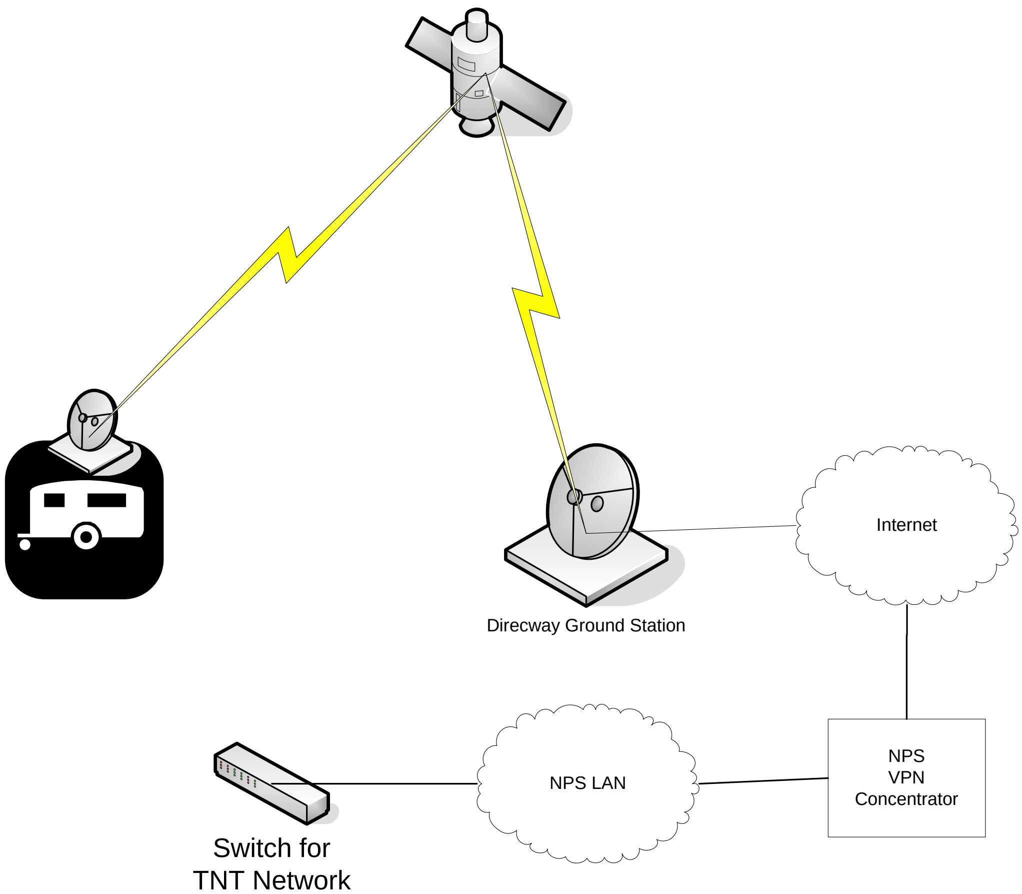

Figure 19. Nemesis in TNT Network

Nemesis connects to its assigned geostationary satellite, which communicates with one of DIRECWAY's ground stations. The ground station connects to the Internet. Through the Internet, Nemesis connects to NPS's VPN Concentrator, which provides access to the NPS LAN. Traffic is routed to the switch that bridges the TNT and NPS networks.

4. iDirect Connection to the TNT Network

Figure 20 illustrates a potential iDirect solution.

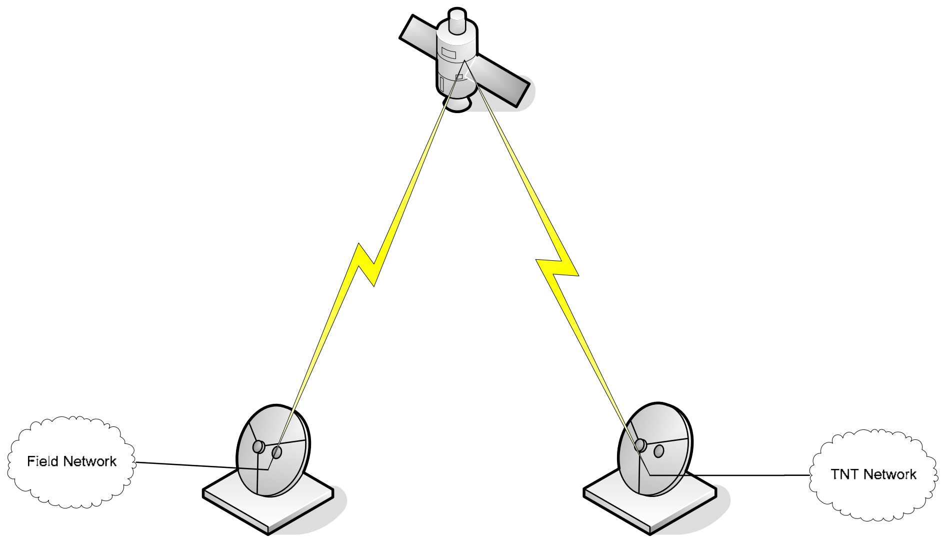

Figure 20. iDirect Private Hub Solution

Outbound data from the field network would pass through the iDirect private hub, which would route the data to the geostationary satellite. The satellite would send the data to the iDirect private hub at NPS, where it would route the data onto the TNT Network. If the two ground stations are outside of a single satellite's footprint, the satellite would route data to a neighboring satellite that has the second ground station within footprint.

While this solution requires the most equipment, this setup would eliminate outside Internet routing, allowing for a simpler network to monitor and troubleshoot.

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IV. DECISION ANALYSIS

Other than using Iridium phones, the CENETIX project prior to this thesis study did not have the ability to communicate with LEO satellites. In addition to experiment set up and execution, infrastructure had to be both purchased, assembled, and tested before experiments could begin. Future operational requirements necessitated testing of existing amateur radio terrestrial network infrastructure in addition to satellite study.

Thesis experimentation occurred in four phases which partially overlapped. First, a ground station had to be constructed at NPS. Once completed, the station could then be used in terrestrial network testing and experimentation, as well as initial satellite uplink and downlink testing. Once these experiments were completed, focus then shifted to attempting a merger of terrestrial and satellite networks. During these phases, the Satellite Network Management team also focused on experimenting with SNMP and ICMP PING monitoring of an Iridium node.

A. MANAGEMENT METHODS USED IN EXPERIMENTS

Much of the experiment methodology occurs in later aspects of research. However, extensive testing of new infrastructure was required. Both testing methodologies and experiment methodologies are covered in this section.

1. Satellite Ground Station Construction and Testing

The Satellite Network Management team's first mission was to establish a fixed ground station capable of tracking a variety of satellites. Immediate goals for the ground station included communications capability on two meter and seventy centimeter bands, software satellite tracking and antenna control, and the capability to use current digital modes to communicate through the satellite. In order to maintain a presence with the rest of the TNT network yet also to maintain security, the station needed to be located in back room of the Gigalab.

The assembly of Groundstation was completed in July 2005. The antenna system mounted on Root Hall's roof required alignment to true north, and calibration between both the motors and the manual control system, and the manual control system and the computer interface. This enables computer control of antenna system movements in the

azimuth and elevation planes. The ability to have this movement allows Groundstation to track LEO satellites from near horizon through satellite overhead, and back to horizon.

Once the antenna control system was calibrated, the Satellite Network Management team proceeded with system testing. The testing methodology was to start with the simplest voice tests in the proximity, then to increase complexity as successive tests are successful. The testing of the voice communications was first conducted on a limited scale with a handheld on the NPS grounds, and then with distant VHF and UHF repeaters in the central coastal California area. Afterwards, we tested the radio's data capability by transmitting and receiving APRS messages and position reports on the nationwide terrestrial APRS frequency, on 144.390 MHz.

While Groundstation is operational, assembly is not complete. Future goals for the station include adding a 1.2 GHz antenna and feed line to the antenna system, and adding another TNC in order to increase frequency agility for ground units. For long range terrestrial networks, an HF antenna should also be installed. In even the longer term, future researchers should consider adding a second two meter radio with an omni-directional antenna, to be dedicated to terrestrial work and freeing up the highly directional Yagi antennas for satellite work.

2. APRS Testing

The satisfactory testing of Groundstation's voice and ability to pass APRS data allowed the next phase of testing. As many of the TNT experiment events occur at Camp Roberts, CA, the next logical step was to test the established APRS system for station coverage en route and on site. In theory, this would provide operational back-up in case of 802.16 system failures. While two digipeaters offer area coverage through these areas, testing was needed to determine any blind spots, particular at Camp Roberts. With Monterey County's topology, Groundstation's antennas are not at sufficient elevation to cover the area.

As suspected, we discovered that the Williams Hill digipeater, N6CP-1, was the critical node for APRS communications between Camp Roberts and NPS. This digipeater covers much of southern Monterey County as well as parts of northern San Luis Obispo County, and is conveniently co-located with TNT's IEEE 802.16 link on

William's Hill. However, this digipeater's position does not provide coverage into the Monterey Peninsula due to mountain ranges running along U.S. Highway 101. To reach into the peninsula, N6CP-1's signal requires a digipeat either through WR6ABD atop Loma Prieta or K6JE-3 atop Fremont Peak. Groundstation has positive connectivity with both of these digipeaters. Figure 21 displays the nodes location.

Figure 21. APRS Digipeater Nodes (courtesy Google Earth)

a. APRS Mobile Mesh – Monterey County

On 03 November 2005, the Satellite Network Management team in conjunction with several emergency communications minded amateur radio operators conducted an experiment to explore the feasibility of using the APRS in a mesh network

architecture. The purpose of this experiment was to determine if one radio among all the radios can be used as a focal point for relay to other networks, particularly satellite networks. As a side benefit, the findings may assist emergency volunteer groups such as the Radio Amateur Civil Emergency Service (RACES) and the Amateur Radio Emergency Service (ARES) in communications emergencies.

The scenario for this experiment was based in the Monterey Bay area, where an earthquake had hit the Monterey Peninsula, and has caused a wide level of destruction. All established digipeaters were down, and mountain access ways were impassable. The County Office of Emergency Services (OES) had asked the amateur community to provide near real time tracking of unit 5901 (the OES sport utility vehicle) as it traveled around the peninsula area, to provide 5901 and the OES the common operational picture, and to ensure 5901 and OES can communicate with APRS with any other fixed station. Additionally, the OES required a seamless digital message-passing network between ad hoc command centers.

The following sites participated in the experiment as the mesh architecture, by turning on the digipeater function in their radio systems:

- LT Richard W. Clement’s House in the Ord Military Community (AE6QE)
- NPS Command SATCOM Station (K6NPS)
- Monterey County OES Auxiliary Communications Officer, Bob Spencer’s House off of Hwy. 68 (W6HMC)
- Monterey County Office of Emergency Services (W6UCS)
- Monterey County Society for the Prevention of Cruelty to Animals (SPCA) Emergency Operations Center (KG6RBK)
- National Weather Service in Monterey (WX6MTR)
- LT Andre N. Rowe’s house in Pacific Grove (KG6YPG)
- Santa Cruz County ARES District Emergency Coordinator Cap Pennell’s house in Santa Cruz (KE6AFE)
- Sam Blaine’s mobile installation, parked in Santa Cruz (KE6ZRW-7)
- LT Richard W. Clement’s Jeep, driven around the area (AE6QE-7)

Other units that sent packets over the mesh include:

- Bob Spencer’s vehicle in Monterey County Health Dept. (W6HMC-7)
- Virginia Spencer’s vehicle in Salinas (W6VLS-7)

Once the experiment was completed, everyone that was able to log their data sent their logs to the Satellite Network Management team. The team compared the logs, and looked for discrepancies which would indicate that units lost the common picture.

b. Alameda Island APRS Boarding Party Experiment

In November 2005, CENETIX simulated a Maritime Interdiction Operation (MIO) boarding on SS Admiral Callaghan, which was moored at the Alameda Island shipyard. In conjunction with the CENETIX experiment, the Satellite Network Management team experimented with maintaining the boarding officer’s position using a 200 mW APRS tracker. AE6QE-7 provided a digipeat relay to the terrestrial APRS network, allowing Groundstation to monitor the experiment from Monterey. The purpose of this experiment was to evaluate how a low powered signal would behave in a metal environment like a ship, and if it was feasible to track personnel on a ship’s main deck. Groundstation logged the event for further study. Figure 22 shows an example of the APRS device used in the experiment.

Figure 22. Pocket Tracker APRS Tracking device (from http://www.byonics.com/pockettracker)

c. *Satellite Digipeater Testing*

The Satellite Network Management team proved Groundstation's capability to interact in all manners of terrestrial networks. The next test was whether Groundstation's antenna system could track a satellite and if the antenna alignment was precise enough to enable communications. In cooperation with the U.S. Naval Academy, the team decided on using Amateur Radio Military Appreciation Day (14 November 2005) to attempt the first satellite contact. During the day, the team enjoyed two separate successes communicating with other ground stations via the International Space Station's AX.25 digipeater.

3. APRS Mesh with a Satellite Asset

In prior experiments, it has been demonstrated that APRS is a robust situational awareness tool. In separate experiments, the Satellite Network Management team demonstrated the ability to form a basic APRS mesh, and also the ability for Groundstation to communicate via satellites. The next step was to attempt using a LEO satellite to relay an APRS mesh to a distant station. For this experiment, Groundstation was set up to communicate through the ISS APRS digipeater, and an APRS portable radio was set up with identical frequency setting as ISS. This enabled Groundstation to receive both stations. The goal was to receive a position report from the portable, and digipeat the signal to ISS, to be digipeated again.

4. Iridium Network Monitoring

TNT uses the Iridium satellite phones for remote sensor monitoring. Once a sensor network receives input, it uses a proprietary RF link to send the information received from the "tripped" sensor to a computer with an Iridium satellite phone connected. The computer uses the Iridium satellite phone as a modem and initiates a data phone call to the NPS Remote Access Service (RAS) server. The Iridium satellite phones have an advertised data capability of 2400 bps. Once the call is made, the Iridium satellite that is overhead receives the signal from the phone and determines its destination. For the Department of Defense (DOD), all Iridium data connections must use the DOD Gateway, which is located in Wahiawa, Hawaii. The first receiving satellite then uses is crosslink capability to connect to the other satellites in the Iridium satellite constellation to reach the DOD Gateway in Wahiawa. Once the relayed signal reaches

the DOD Gateway, the call is then passed to the Plain Old Telephone System (POTS) and routed accordingly to reach the NPS RAS. Upon reaching the NPS RAS, the user requesting access is authenticated and granted access to the NPS network. Once on the NPS network, the PPP adapter will receive an IP address on the 131.120.49.X subnet. The sensor data is then delivered to the ISGIANT server in the CENETIX Lab.

Once the Satellite Network Management team discovered how TNT's 192.168.X.X network interfaced with NPS's network, and the address space of the RAS, it became easy to propose a potential monitoring solution for Iridium nodes. Within Solarwinds the team configured the Network Monitor to poll at an interval of 20 seconds if no error were detected and every 10 seconds if there was a failure of the connection. To discover the IP address of the Iridium data connection the team utilized the SNMP discovery tool built into Solarwinds.

The framework for the experiment was to have a computer dial-in to the NPS RAS via the Iridium satellite phone. Once the connection was established with the NPS RAS the computer would be assigned an NPS IP address. Once the notebook had an IP address, the SNMP discovery tool would be used to identify which NPS RAS connection was the computer dialing in via Iridium. With the IP address, the Network Monitoring tool would then be started to collect connectivity information.

B. EXPERIMENTS AFFECT ON MISSION EFFECTIVENESS

As stated previously, the goal of this research was to determine how to best use LEO satellites in conjunction with established terrestrial networks in a tactical environment. While LEO satellites can provide communications to remote locations, their usage can often complicate a communications plan. Additionally, and particularly with amateur radio satellite assets, the Federal Communications Commission (FCC) maintains strict guidelines as to what communications can be passed over amateur radio links.

1. Terrestrial APRS Operations

While originally the Satellite Network Management team had expected to explore APRS as one of the amateur radio satellite protocols, the team quickly realized potential implications in using APRS as a robust terrestrial protocol. The considerable sized pool of amateur radio operators and well established network of digipeaters provide a reliable

position reporting and messaging platform that can provide backup to other networks in the event of failure. As soon as Groundstation transmitted its first frame, it literally placed NPS on the map, and became a regular participating node on the APRS network. With the ability to serve as a back-up fill in digipeater, it provides redundancy for much of the peninsula.

a. Mobile and Portable APRS Operations

While the installation and operation of mobile and portable APRS stations are not in themselves experiments, using the equipment operationally places impact on mission effectiveness. During procurement of the equipment, the Satellite Network Management team attempted to maximize both functionality and usability. Both the TM-D700 mobile and the TH-D7AG portable combine radio and TNC functionality, and thus can serve as stand alone stations. Still, both units require a GPS feed for position reporting while moving. While computer connection is not necessary for these units, they work very well with computers.

Portable units place the greatest impact on the individual. The user must make provisions for carrying the radio, the GPS unit, and possibly a Personal Digital Assistant (PDA). Should the radio be used without the PDA as in Figure 23, the user should be prepared to frequently hold the unit while using the chat functionality. Messages are entered in a similar manner as Short Message Service (SMS) messages on cellular phones, less the phone's helper functions. If the GPS units are not held by the user, an external antenna may need to be added to maintain GPS lock. Additionally, the user must keep the GPS unit accessible if he/she wishes to know the positions of his/her fellow team members. This places an additional burden when the operator may be required to carry other field gear and weapons.

Figure 23. Kenwood TH-D7AG and Garmin eTrex Legend Portable APRS Station

Operation of the mobile radio is similar to the portable, but the components may be permanently mounted in a vehicle to maximize ease of use. Messaging while driving is dangerous, so if the driver has to operate the radio, he/she will have to stop to respond. Like the field user, the GPS can be used for both viewing team members' positions and vehicle navigation. Displayed in Figure 24, the APRS station consists of the radio control head to the left of the steering wheel, the GPS unit on top of the dash board, and the optional computer. Operation with a computer will be similar as what police officers use daily as their mobile display terminals (MDT). In order to view the screen in the vehicle, one should consider the requirement of using the computer in bright sunlight when purchasing.

If possible, a passenger should operate the computer and APRS messaging functions. Using a computer while driving can be a dangerous challenge. It requires additional training and a thorough knowledge of the APRS software's functionality.

Figure 24. AE6QE-7 APRS Station with Computer Installed

b. Single Unit APRS Testing at Camp Roberts

Prior to embarkation, the test vehicle and Groundstation conducted connectivity checks to ensure both sides functioned normally. To simulate portable radio equipment, the test vehicle's output power was set to 5 watts, the standard high power setting for a handheld radio. During the transit to Camp Roberts data communications using APRS were more than adequate. Via digipeater relays, the test vehicle was able to maintain communications with Groundstation through APRS chat messaging and position reporting. At Camp Roberts, excellent chat connectivity was maintained through the commute to the TNT test location and while on site.

Previously, TNT experimenters could only use cellular phones to maintain connectivity during transit to Camp Roberts. While not a critical requirement, this redundancy in communications and position reporting provides a higher degree of safety for those experimenters both willing and capable of employing APRS. At Camp Roberts,

experimenters often experience poor cellular phone connectivity, making experiment coordination difficult when the 802.16 backbone fails. Having an APRS node at Camp Roberts can provide limited chat redundancy for the 802.16 backbone

c. APRS Mobile Mesh – Monterey County

The next progression in experimentation was to test the feasibility of a multi-node APRS mesh. Based on the scenario outlined earlier, the three requirements for success was that the OES maintain situational awareness of where the Jeep was at all times, that all units of the mesh have full situational awareness in a Common Operational Picture, and that the OES can contact any mesh station.

Through the mesh links, the OES was able to track the Jeep throughout the entire trip. However, the OES was unable to communicate to the Jeep over 75% of the time. The mesh was divided along a ridge passing between the Monterey Peninsula and Salinas. However, two different one-way links developed between the two meshes, allowing full situational awareness to all units east of the ridge. This left all units west of the ridge without a picture of the Hwy. 68 corridor and the OES.

One interesting station was Bob Spencer's truck. It was able to receive and transmit to both of the meshes, but prior planning had dictated that it not have its relay mode activated. Would this station have been activated instead of the OES, the two meshes would have joined through this station. RACES personnel later discovered faulty coaxial cable between the OES APRS radio and its associated antenna causing transmission and reception difficulties. Based on proven simplex voice connectivity between NWS Monterey and the OES during 2005's Simulated Emergency Test, the Satellite Network Management team hypothesizes that with the repairs now made, a repeat of the experiment would create a reliable mesh.

Figure 25 depicts the links that formed the mesh networks during the experiment. Implementing an APRS mesh such as this drastically increases the survivability of a network in a disaster situation. Mission effectiveness of APRS was maintained, despite losing critical digipeaters in the APRS network that ordinarily enables communication between the stations. The downside to this, however, is that

rather than a couple of digipeaters retransmitting the data, each node is required to do so, thus increasing the network load and the potential of frame collisions.

Figure 25. Inter-Node Links During Mesh Experiment

Should Groundstation have been employed to relay this experiment's data to satellite, it could have successfully relayed 9 of the 11 nodes' data. Without the mesh architecture, it could have only relayed 5 of the 11. With repairs to the OES station, the team hypothesizes that all 11 could have been relayed.

d. Alameda Island

Upon commencement of the experiment, the Boarding Officer's APRS device was activated. It was preprogrammed to send its position information to AE6QE-7, which provided digipeater relay to any digipeater using the standard WIDEN-n protocol. Once an established digipeater received the data, it would relay the data to digipeaters within Groundstation's reception area. The Network Satellite team correctly hypothesized that the data would traverse W6CX-3 in San Francisco and WR6ABD on top Loma Prieta in order to reach Groundstation. Figure 26 displays the nodes' positions.

Figure 26. APRS Nodes Used in the Alameda Experiment (courtesy Google Earth)

Throughout the experiment, Groundstation maintained situational awareness of both the AE6QE-7 digipeater and the boarding team tracking device. Chat capability was tested and was successful in passing short messages between AE6QE-7 and Groundstation. Since the tracking device possessed no messaging and reception capability, no chat testing occurred between the boarding team and Groundstation.

This experiment exhibited a proof of concept for later studies. Using a low powered tracking device could allow exterior monitoring of critical personnel's positions. However, the range during this experiment between AE6QE-7 and the tracking device provides no conclusive evidence in the usefulness of the tracking device. While the tracking device has been useful in tracking vehicles during the Big Sur International Marathon, the combination of the ship's communications and navigation systems, low elevation, the ship's cargo and hull potentially providing a multi-path environment brings a large margin of uncertainty that must be more thoroughly investigated during at-sea trials.

e. FCC Restrictions

Perhaps the most significant obstacle to effectively using APRS networks for operations comes from FCC regulations. Title 47 of the Code of Federal Regulations (CFR), Part 97, stares that prohibited transmissions include:

> Communications in which the station licensee or control operator has a pecuniary interest, including communications on behalf of an employer…[and] Communications, on a regular basis, which could reasonably be furnished alternatively through other radio services.[71]

While experimenting for the purpose of advancing the radio art is encouraged in the amateur radio service, the question arises pertaining to the allowance exercise control communications by military personnel and institution employees (regardless of license issuance) for non-amateur radio experiments.

Should a requirement for operational or tactical data to be passed by APRS come into existence, the APRS network should be established in another radio service. Methods of doing this include:

[71] "Part 97 – Amateur Radio Service", 47CFR Part 97 (Washington: FCC)

- Connect radios licensed in another service to TNCs
- Receive National Telecommunications and Information Administration's (NTIA) approval to use modified Kenwood TS-2000s, Kenwood TM-D700s, and TH-D7AGs in the 136-144 MHz and 148-150 MHz federal government frequency bands. These radios are easily modifiable, but using modified equipment without permission is illegal.
- Contract with a provider to make an APRS capable commercial radio.

2. Relaying APRS to a Satellite

Having proved that one node in a mesh can possess a complete COP, the next step was to determine if a mesh node could relay the mesh network to a satellite. During the time period of this experiment, ISS was the only APRS-capable space asset operational. For a mesh network, the ISS is a poor choice for satellite relay, due to its uplink and downlink having different frequencies. This requires that the relaying ground station have separate radio ports for ISS and for the mesh, which works best operating on a single frequency. For this experiment, this problem was overcome by setting the handheld field unit to the same frequency set as the satellite relay, allowing Groundstation to communicate with both units. This is depicted in Figure 27. This solution would not work for a mesh environment, since Groundstation would be the only station capable of communicating with any other unit.

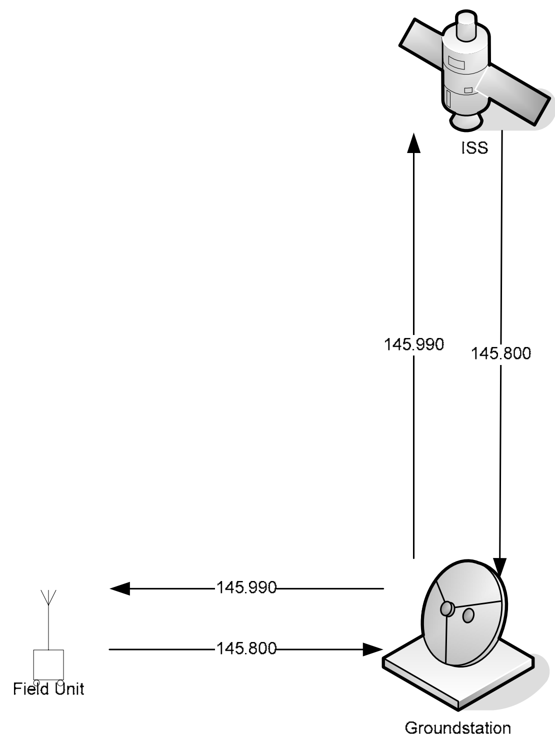

Figure 27. Frequencies used in Satellite Relay Experiment

Prior to overhead time, Groundstation and the field unit were tested to insure proper operation. Within the approximately eight minutes of overhead time, the ISS digipeater successfully relayed two APRS position reports from Groundstation and two reports from the field unit, relayed through Groundstation. While it would have been more desirable to have received more than these relays, it proved the ability nonetheless. In each pass, a remote location could receive position reports from all the mesh units, and briefly chat with one or more stations. The Satellite Network Monitoring team believes that part of the reason more reports could not be relayed was due to ISS remaining near to the horizon for the pass, as well as obstructions blocking Groundstation's antennas' horizon view.

3. Iridium Network Monitoring

The progressive steps that were identified earlier worked as expected. The Network Monitoring tool was able to monitor the state of the Iridium dial-in connection. With the link being idle the Networking Monitoring tool showed a latency of 1600

milliseconds and approximately a 30% packet loss. The speculation of why the latency was so high varied. One potential reason was due to the distance the connection was traveling. Even though the connection from the notebook was originating in Monterey it had to go over to Hawaii via satellite. A second possibility for the high latency was the POTS service. The phone company has various methods of connecting a phone call from Hawaii to California. Additionally, satellite hand-off negotiation can cause delays, as each Iridium satellite is only overhead for up to 15 minutes at a time and calls are constantly being handed-off during a long connection. Another potential cause of the high latency could be also due to the Iridium Gateway in Hawaii. Call handling at the gateway station could also contribute to the latency problem.

After monitoring the connection at idle, the next progression was to monitor the connection during a file transfer. As the Satellite Network Management team started a file transfer, latency and packet loss increased. After approximately two minutes, Solarwinds was calculating a packet loss of 90%. After five minutes, the Iridium satellite phone connection was lost. The connection was then reinitiated by the computer and the idle connection was monitored once again for stability. Once the file transfer was started the same problems began to occur and the connection was then lost.

Since Iridium operates via a PPP adapter at 2400 bps, diagnostic tools used to normally troubleshoot network connections only add to the already stressed load on the connection, or cannot even see the connection. Monitoring tools such as the Solarwinds suite may be used for network discovery and to display network statistics while the connection is otherwise idle, but effectiveness of the Iridium node may be hampered if Solarwinds attempts to monitor the node while a file transfer is occurring. In future experiments, the Network Monitoring tool should not use the normal TNT settings for monitoring the Iridium connections. It is recommended that the normal polling period be adjusted to every two minutes and when problems are discovered to poll every minute. Adjustment of these settings will potentially lessen the amount of traffic on the slow Iridium link. Another potential solution is to install a middleware application on the node to intercept SNMP requests and filter the data returned to the SNMP client. The middleware application would only allow the pertinent information pass to the Iridium

link lessening the amount of traffic on the limited Iridium link. The other less important information would then be written to a text file for later review.

V. IMPLICATIONS OF RESEARCH

As technology for geostationary communications satellites continues to improve, the once large appeal of the LEO communications satellite comes into question. Even LEO satellites' practicality of communications with low gain, integrated omni-directional antennas on portable devices such as satellite phones is now shared by higher orbit satellites. Thuraya Telecommunications Satellite Company has been providing similar services as Iridium over Europe, the Middle East, Africa and parts of Asia using geosynchronous satellites since 2001.[72] As discussed previously, CENETIX has already starting using geostationary satellites for high-speed Internet connectivity. Currently, the ATM LEO satellite idea is still in the design phase of development, and may never become implemented should telecommunications companies use the same antenna technology as the Thuraya satellites, and apply it to a geostationary satellite service providing Internet connectivity.

The question thusly may not be one of how to better provide services with LEO satellites. Instead, it may be how to add communication capabilities on LEO satellites with other missions for redundancy and in-theater communications targets of opportunity for low priority units and for service member quality of life.

A. HOW TACTICAL UNITS MAY EMPLOY LOW EARTH ORBITING SATELLITES IN OPERATIONS

As both the speed and necessity of communication increases, more military units have turned to satellites for reliable communications with other units. While geostationary satellite assets provide the bulk of services, for the interim LEO satellites still offer the Department of Defense several possibilities.

1. Sensor Feedback

Since its conception, TNT teams have experimented with various deployable sensors. One desired end state for these sensors is the flexibility to be quickly deployed anywhere. These sensors are small, and will operate in remote areas of the world without terrestrial communications options. As of now, the sensors under experimentation in

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72 "Technology" [web site] (cited 13 FEB 06); available from World Wide Web @ http://www.thuraya.com/tech

CENETIX use Iridium satellites to communicate with the rest of the network. Currently, Iridium offers the only satellite service for cellular type communications on a truly global scale. Global coverage allows a single satellite solution for these sensors, as the development moves from prototype to mass production.

Even with the complications of network management over Iridium links, the connection is adequate enough for small data exchanges. While imagery may be desirable and is even possible given enough time, smaller data sets like vibration detection and movement will require fewer packets over the connection. To avoid enemy discovery, RF transmissions can be minimized by programming sensor devices to connect on sensor detection, upload the obtained data, and disconnecting instead of constantly maintaining link connectivity. To avoid potential latency problems since the signal will most likely travel through several satellites, the User Datagram Protocol (UDP) or other connectionless datagram protocols should be used as much as possible to avoid connection timeouts. Since connections might drop, sensors and the controlling computers should have the capability to continue data transfers from the last successful packet before the connection drop, rather than starting the transfer over again.

Currently, some sensors operate in clusters. Once a remote sensor detects activity, it relays its data to a controlling unit, which sends the data through the satellite connection. Future generations of sensors should each relay their data directly through the satellite link, and allow computers at more secure locations compile the data. This would eliminate failure of an entire sensor cluster should the control station fail.

2. Communications while Traveling

As mentioned before, current usage of geostationary satellites requires highly directional antennas that are pointed at the satellite to communicate. For military units in transit, these requirements will either mandate expensive motor-controlled rotators to maintain the link, or for the unit to stop, set-up, communicate, and breakdown. While motor-controlled mounts are cost prohibitive for mass deployment, stopping travel to communicate places the unit in a potentially hazardous situation and slows the overall speed of advance.

One stop-gap solution for this problem is either to message a unit via Iridium SMS or use a voice phone call to notify the unit whenever a connection is required. The unit could then dial into a RAS via Iridium to download e-mail or to chat via an Internet Relay Chat (IRC) server or UNIX Talk connection. Otherwise, the unit's computer can be set to dial in on fixed intervals to download lower priority e-mail. This way, stops for a geostationary satellite connection can be minimized, and used only for larger uploads or downloads.

3. Low Priority Communications

While a significant portion of data traveling between deployed units and the outside world is of high priority, there is still much data that is not as critical. Some of this lower communications can be daily reports to the chain of command, training scheduling once the unit returns home, personnel management, and even soldier/sailor/Marine Quality of Life e-mails to the family members. While connected to a fast connection, such messages may take relatively little space and time on the connection to transfer. However, if the throughput is limited, higher priority messages may continue to push lower priority traffic off the queue.

LEO satellites offer a couple of solutions to lower the burden of low priority traffic on high priority assets. Store-and-forward capable satellites that are overhead a few times a day can take e-mail messages and relay them to a forwarding station within hours, and pick up replies to be delivered. A satellite with a transponder could provide short periods of non-priority voice and data communications within theater. Through a digipeater, a theater commander can receive position reports from non-critical units not otherwise tracked a few times a day.

4. TacSat Usage

As discussed previously satellites in the TacSat project are predominantly developed to provide detailed imagery of assigned areas. In order to provide this mission, the satellites must possess a store-and-forward type capability in order to capture the image and hold it until it passes over a control station. If the imagery buffer is emptied once the ground station downloads the data, other data can conceivably be uploaded, which could be broadcasted until it clears the buffer for the next mission. Non

critical items, such as news reports, sports scores, and other Quality of Life information can be broadcasted by TacSat over deployment areas.

B. RECOMMENDATIONS FOR SATELLITE PAYLOADS AND GROUND STATION CONFIGURATIONS

When it comes to satellite communications, CENETIX experimentation is still very much in its infancy. As NPS begins reaches out to Stanford University and other academic institutions to conduct project partner ships, future CENETIX teams will have a chance to influence satellite payload decisions. Should CENETIX continue amateur radio satellite experimentation, it would be in the project's best interest to partnership with amateur radio communities such as The Radio Amateur Satellite Corporation (AMSAT) to potential influence future OSCAR payloads.

1. APRS Constellation

Currently, Satellite APRS's greatest weaknesses are the number of satellites in orbit and the varying frequency and throughput values. Currently, ISS has a digipeater for APRS and UI AX.25 frames at 1200 bps AFSK, 145.800 MHz downlink and 145.990 MHz uplink. PCSAT, suffering from extremely low batteries and only operable under peak sunlight, provides an APRS digipeater on 145.825 MHz at 1200 bps AFSK. PCSAT-2 on board ISS operates in the same mode as PCSAT, and is at times subject to power depletion when its solar cells do not receive adequate solar exposure. AO-51 "Echo" operates in an experimental digipeater mode with a 435.300 MHz downlink and a 145.860 MHz uplink at 9600 bps FSK. Of these four satellites, two of them are co-located, and two of them share identical settings.

Most often, amateur radio satellites serve as experiments with minimal regards for other satellites in existence. As a result, no common data or voice modes for these satellites exist, and multimode radios are required to exploit the various modes. With the proliferation of relatively inexpensive APRS tracking devices and various manufacturers producing APRS capable two way radios, combined with APRS's modern routing protocols, APRS makes an ideal protocol for satellite communications. A common protocol would provide a greater service to the amateur radio community, and would provide another tool to the emergency communicator's toolbox.

The ideal vision for amateur radio satellites would include a constellation of satellites, carrying both favored experiments and APRS digipeaters. Either the APRS Working Group or AMSAT would decide a common set of settings for these digipeaters, allowing trackers and other ground station radios to have these settings programmed. Then, regardless of which satellite is overhead, the ground station could communicate with it. These satellites could feed into the APRS network through the use of satellite gateways connected to APRS servers, just as is done currently with the PCSAT satellites. With a constellation, cross-talk between satellites should be avoided. Since more users would wish to try the satellite constellation, the working groups should consider using 9600 bps FSK to minimize collisions and maximize users' potential to communicate.

2. Store and Forward Systems

Another AX.25 based system that should be considered is the use of store-and-forward systems. As discussed previously, store-and-forward systems still have potential in lower priority communications. Additionally, in the amateur radio community, store-and-forward systems avail themselves to use by the National Traffic System (NTS), an American Radio Relay League (ARRL) field organization.

Again, creating a standard is the key for these systems. The constellation should have one frequency and one mode for users to access the bulletin board systems. Ease for the end user is key, in case the user finds himself/herself in a situation without access to satellite overhead times and the various settings.

3. Experimental IEEE 802.16 Routers

Currently, an 802.16 backbone stretching from Camp Roberts to NPS is the critical link for TNT experiment operations. Without it, the Gigalab NOC is rendered useless in monitoring and recording experiment data. Multiple sensors in the area along with using collaborative packages such as Groove require high throughput rates that may overwhelm Nemesis's DIRECWAY satellite link. With the desire for a backup to the terrestrial backbone, with TNT's mission to explore new possibilities, the team is considering the possibility of using an 802.16 router to extend the signal.

While the experiment is certainly possible, design of the entire system must be carefully considered and may require proprietary hardware. Doppler shift between the ground station and the satellite at 5.8 GHz is significant, and the frequency ranges of the

shift would depend on the orbital altitude. This will require ground station transceivers to have the capacity of changing frequencies to compensate for the Doppler shift. Free space power loss over the distance between the satellite and ground station will also be a factor, and may potentially require RF power and antenna gains beyond FCC limits for the ground stations. Should gain exceed 47 CFR Part 15 allowable amounts, the stations and their users may operate under amateur radio regulations, given the users have the appropriate licenses.

Again, researchers might consider a constellation of satellites. Satellites placed in close orbits can expand the given time for the experiment. In any case, experiments will have to be scheduled relative to overhead times.

4. CENETIX Mobile Amateur Radio Ground Station

Currently, the Satellite Network Management possesses a complete APRS mobile radio station, ready to be installed in a vehicle. With this system, a user will be able to uplink to ISS and the PCSATs. However, with the license requirement for station operation combined with determining the best usage of this station have currently precluded its installation. Provided below are some possible options.

a. Light Reconnaissance Vehicle (LRV) Option

The LRV could make an excellent platform for the station. With its telescoping mast, a mounted omni-directional antenna would have a better view of the horizon. The LRV's position could be monitored through both terrestrial and satellite APRS systems. The FM voice capabilities of the radio can be used to keep in touch with the NOC, or can be used as a cross band repeater for the portable units. The station can also be used as a satellite relay station and a field digipeater for portable units in the area.

However, space in the LRV becomes an increasing issue as additional equipment is mounted aboard. While the transceiver body can be hidden out of sight, both the control head and the GPS unit will require mounting in a usable position. Antenna spacing becomes a concern, to avoid de-sensing and front-end overload of the various radio receivers on board.

Based on past and present usage, thesis students will be the most significant users of the LRV. Using the station would require at least one person at the

station to possess a Technician class amateur radio license. Otherwise, the station would require adequate securing to prevent unauthorized usage.

b. Nemesis Option

The integration of this station into the Nemesis NOC would provide a very robust APRS capability. All workstations both on board Nemesis and operated through the Nemesis router could benefit from the APRS operational picture through setting up one computer as the radio interface, and sharing the radio data over the network. Additionally Nemesis can provide an Internet gateway for the station, allowing any APRS experimentation or operation to be viewed worldwide and allowing remote units to communicate directly with portable APRS stations using Nemesis' services. Additionally, Nemesis could be used as a satellite gateway for the amateur radio satellites, expanding the effective coverage area for them in disaster or remote locations. Other possibilities include Echolink or the Internet Radio Linking Project (IRLP) Voice over Internet Protocol (VOIP) connectivity to allow portable stations in the area to communicate with distant stations over voice.

While this would be the most ideal solution should Nemesis ever be deployed for a disaster again, the licensing requirement remains in effect. Additionally, workstations viewing the APRS operational picture would have to set up as receive only stations for non-licensed personnel. Mounting an antenna for the radio would require a permanent solution, since magnetic mount antennas cannot be used on Nemesis' fiberglass body. Additionally, CENETIX does not have sole control over Nemesis, which would create difficulty in station accountability.

c. Construction of a Portable Station

If neither of the above solutions is ideal, the station can become portable. In several amateur radio emergency communications groups, mobile radios are integrated with batteries and power supplies to form stations that are deployable anywhere. This would allow for a quick deployment and removal in Nemesis, the LRV, a Rigid Hull Inflatable Boat (RHIB) if made water proof, or even the Camp Roberts Tactical NOC. Figure 28 displays one possible implementation of this solution.

Figure 28. Emergency Communications Portable Solution (from: The Box: Portable Emergency Communications Station Ideas)

Portability of the station adds to convenience and security, but detracts from permanency and safety. If the portable station uses an antenna attached to the case, the electromagnetic field exposure to the user would exceed FCC mandatory limits. Wiring both inside and outside the enclosure should be inspected prior to each usage to prevent fire hazard. Unless additional measures are taken each time, the station will not be RF or DC grounded, creating a potential of equipment damage, electric shock, and RF burns.

5. Long Term Vision for Groundstation

Groundstation has the potential to become NPS's premier satellite communication facility. While the station provides basic functionality now, improvements should be made as time and money allow. Newer satellites such as AO-51 and AMSAT-Phase 3E (P3-E) have increased throughput capability up to 76 Kbps, which will require upgrades to the transceiver equipment and acquisition of better TNCs to utilize this capability. A 2.4 GHz down-converter and associated antenna will also be required to receive the higher throughput downlinks. P3-E will also offer C, X, and K band voice frequencies.

As TacSat development continues, CENETIX may elect for a capability to directly download imagery. While the station's TS-2000X can receive military UHF frequencies with low receiver sensitivity, the download capability may require a separate equipment installation and a better antenna for that frequency range. An AN/PRC-117

radio could be added to provide functionality for military UHF satellites should CENETIX ever need that ability with TacSat or future experiments.

Groundstation provides a good platform for IEEE 802.16 satellite experimentation as well. The antenna platform would sustain a fairly small 5.8 GHz dish antenna. The Ethernet Bridge can be connected to the CENETIX network easily for GIGALAB monitoring, or through the Groundstation computer.

C. MANAGING NETWORKS OVER AMATEUR SATELLITES FOR USE IN INTERNATIONAL DISASTER COMMUNICATIONS

As previously stated, most of the network management tasks for amateur satellites have to be performed manually by users. While automatic enforcement of management rules is currently impossible, organizations wishing to employs these satellites in disasters must coordinate with satellite owners, then distribute the protocol to as many users as possible. Future satellites can provide automatic enforcement in emergencies but the protocol must be developed in the satellite's design phase, and a common protocol should be in place for ease of ground station set up.

In disaster communications, amateur radio messages are sorted by the priority levels of emergency, priority, and welfare. Emergency messages are the highest priority, and pertain to urgent life-or-death situations. Priority messages are often official in nature, originate from a served agency, and must be delivered within a given period of time. Welfare messages allow for family notifications of disaster victims' disposition.[73]

1. APRS

As APRS units become more available, more users will be attracted by the inherent beaconing availability for emergency situations. Unfortunately, a satellite gateway must be in the same footprint as the beacon in order to provide a relay onto the terrestrial network. Since active gateways will most likely be some distance from a disaster area, the two stations may share a footprint for only a fraction of the total overhead time at either station. Communications between stations will most likely be impossible because of inefficient antennas on the field station or beacon preventing horizon level contact with the satellite.

[73] Dave Colter, Amateur Radio Emergency Communications Course: Level I, 2nd ed., (ARRL: 2003), 56.

Before the disaster, radios should be set up to work with PCSAT and PCSAT-2. Stations with emergency messages should wait until the satellite is overhead to begin transmissions to conserve power if possible. The beacon comment should describe the nature of the emergency. Once overhead, the station should transmit beacons every 30 seconds to ensure the message is received by a satellite gateway. If the station settings allow for an offset in messaging, the user should enter a randomly chosen number less than 15 seconds for an offset to minimize collision potential.

Only emergency beacons in the affected area should be transmitted. Since position beacons are not acknowledged, a user should only rely on this method if all other methods are exhausted. Emergency communicators entering the affected area should have other methods of communication, and should not use the satellites if possible.

Future satellites should incorporate priority filtering into the digipeater in order to enforce this usage in disasters. Should more APRS satellites become available, emergency communicators can consider passing priority traffic and using them for chatting as the emergency beacons become fewer.

2. Store-and-Forward Packet Bulletin Board Systems

As of 18 January 2006, ISS and a satellite designated as GO-32 operated bulletin board systems.[74] These bulletin boards are similar to ones used terrestrially by NTS to electronically pass formatted messages. Users in affected areas not able to pass traffic through other means may attempt to use these systems. NTS volunteers outside the affected area can access these bulletin boards and relay messages to their ultimate destinations.

When a large disaster occurs, world-wide routine usage of these satellites should be terminated, and as much message space as possible should be afforded to messages originating or terminating in the affected area. Messages should be posted to the bulletin board based on priority, which would be directed by emergency communications managers.

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[74] "OSCAR Satellite Status Summary as of 18 January, 2006", [web site] (cited 15 FEB 06); available from World Wide Web @ http://www.amsat.org/amsat-news/satellites/status.php

Winlink 2000, an amateur radio e-mail service available through the Internet, HF PACTOR, and VHF AX.25, is rapidly becoming an instrumental tool for emergency communicators to have Internet e-mail connectivity. Future satellite developments should consider implementing a Winlink 2000 message board which satellite gateways attached to the Winlink network could automatically interface with. When atmospheric conditions in the affected area preclude HF communications, these satellites could pass e-mail traffic as needed.

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VI. CONCLUSION

Through the course of researching, experimenting, and writing this thesis, the Satellite Network Management team quickly discovered that the potential of satellite integration into TNT is limitless; indeed, satellite communications may eventually replace all aspects of the terrestrial infrastructure and reduce the deployment size to just laptops and sensors. As a result, the research herein addresses the vast range of possibilities without having the opportunity to research any subtopic in depth.

Through the course of TNT experiments, researchers have relied on Iridium services to relay information from remote sensors to the test bed network. Emphasis was placed on the sensor technology development and communications protocols for passing data, with minimal regard to the communications path. In January 2005, a group of students was asked to address the possibilities of applying management techniques to these sensor nodes and to explore other LEO satellite communications capabilities, particularly with amateur radio research satellites and the emerging TacSat program.

Because of the way Iridium-connected sensor node data travels through so many networks, they were an anomaly to the routine monitoring functions employed at the various NOCs. CENETIX research heavily relies upon Solarwinds SNMP Discovery and Network Monitoring tools to track network stability, configuration, and functionality, making the monitoring of Iridium sensor nodes through the same program desirable. If implemented properly, Solarwinds enabled the discovery of a remote sensor network and monitoring its connection statistics through the network. Finding the right implementation became the first facet of the team's studies.

In 2005, the first satellite of the TacSat program settled into orbit and started performing image collections as designed. A second challenge assigned to the Satellite Network Monitoring team was to explore potential management techniques and uses of the future TacSats,. As a national asset whose mission capabilities are in use to support the international war on terror, combined with the first satellite possessing virtually no communications relay capabilities, OSCARs became the second focus of study, in hopes to apply lessons and experiences from these assets to future TacSat payloads.

CENETIX however did not possess the capabilities needed to communicate with OSCARs. A secondary requirement for the Satellite Network Management team was to design Groundstation, an amateur radio station capable of communicating with most of the OSCARs in orbit and expandable enough to accommodate future satellites. Once Groundstation was completed, the team discovered that very few of the satellites in orbit could be used as a part of a routable network. All the satellites possessing processing abilities enough to intelligently digipeat utilized the AX.25 protocol, and relayed UI frames.

Before beginning satellite experimentation, the team decided to use the APRS system for equipment testing, as APRS is one of the most robust AX.25 networks in use worldwide. While viewing the station test, CENETIX management realized the potential behind utilizing APRS networks, both terrestrially and through satellites, as a backup situational awareness and experiment coordination tool. As a result, the team narrowed the focus to AX.25 satellite experimentation.

Also during 2005, CENETIX made global partnerships, with the potential of conducting experiment operations in Canada and Europe. One consideration for expanding the existing TNT networks to these remote locations was the use of geostationary high-throughput data satellites. The team started meeting this challenge by researching different providers of potential equipment. In November 2005, a CENETIX experiment on Alameda Island, California required satellite connectivity, which was delivered by a newly installed DIRECWAY system on board the Nemesis Network Operations Center.

September 2005 brought new challenges to CENETIX and other network studies groups at NPS, when Hurricane Katrina devastated Louisiana and Mississippi. While deployed to Bay St. Louis to assist in establishing emergency Internet connectivity, one team member noted how almost every piece of communications in and out of the area was happening either through commercial and government satellite services or through amateur radio operators. With cooperation from local RACES and ARES officials in the Monterey Bay area, the team researched possible ways that amateur radio satellites and APRS networks could be used in future disasters.

Due to its growth over the past year, CENETIX must now consider satellite integration to support its continued expansion. However, management over these links will remain a challenge due to a lack of satellite control. While SNMP can easily monitor IP related statistics, these statistics take into account not just the end node, but the entire network between the node and the CENETIX network interface. Specific conclusions of the various researched satellites solutions are offered below.

A. AMATEUR RADIO LEO SATELLITES

Amateur Radio LEO satellites have proven to be a quick and easy implementation method to gain research opportunities to satellite voice and data communications cheaply. The proof of this is the number of universities or non-profit organizations that can construct and have the satellites launched. The LEO satellites provide some ability to conduct voice and data operations but lack enough time to support reliable connections. The estimated overhead time for a LEO satellite is only eight to fifteen minutes, which does not allow for much error on the part of the ground unit. The one solution for this problem, while still staying in a LEO, is to have a robust constellation of satellites that have the ability to cross talk and perform hand-offs of the connections once the ground user has decreased to a certain signal strength. This alone makes LEO not the best solution for data and voice communications. Another potential solution would be to have each LEO satellite having a large enough onboard memory to buffer the data or voice communications that it received from a ground unit until it could relay it to the recipient or a satellite ground station that could provide another method of delivery. The second potential solution has more chance of success in implementation but would require a method of ensuring the timely delivery of its buffered traffic.

The research desires of those who launch these satellites are often different from one another, creating continual sets of incompatible frequencies and modes. In order for any constellation of OSCARs to succeed in operating in an operational environment, common frequencies and modes must be put in place. Then, the ground stations' task of communications is significantly simplified, which would result in greater liability in a disaster or tactical environment. Through the U.S. Naval Academy's research of the APRS protocol in their own satellites, they discovered that APRS is a suitable protocol for both satellite-to-ground station and satellite-to-satellite relay. The Satellite Network

Management Team's own findings conclude that if more APRS satellites arrive in orbit, they can serve as a periodic backup for maintaining a "blue force" common operational picture and short messaging.

Until larger constellations are in place, OSCARs, particularly the ISS and the PCSATs, may be used in research to provide platforms for proof-of-concept operations. In operations, digipeater type satellites offer minimal usage due to their limited time overhead, and should not be trusted to relay critical data to other stations that may or may not be in the same footprint. Store and forward networks may provide an alternative for delivering NTS style formal messages between stations in different geographic locations.

B. APRS FOR SITUATIONAL AWARENESS

Situational awareness (SA) is pivotal at all levels of command and control (ie. tactical, operational, and strategic). Most units report their position and intended movements via voice communications, messages, or via GPS transponders. From the experiments conducted in conjunction with the CENETIX project and the TNT experiment, we have concluded that APRS is a viable alternative to the previously mentioned methods of maintaining situational awareness at a tactical level.

The experiments conducted slowly built upon each other and led the conclusion that APRS is a very capable SA tool. It can provide a mesh network, a star-and-hub topology, or predefined network path. Features include position information for each node, the ability for members of the network to plot points, use chat messages, send email, and allow voice communications. It can be an ideal solution for not just military operations but also for disaster operations. Field operators need only to either setup a digipeater station that can provide coverage for the area of operations or setup the end nodes for mesh operation, and equip other field members with the necessary equipment. An operations center, part of the network, can then maintain position information on all of its operators in the field. Entire network pictures can be relayed by a capable ground station to a satellite, so that remote participants can view the same picture as those in the field.

APRS however has some serious limitations in a mesh environment. The number of fully participating stations is currently limited to nine station by the protocols

programmed into APRS software and TNC firmware. Additionally, APRS normally operates in the terrestrial network at 1200 bps. An APRS mesh produces up to seven repeats of each transmitted frame in order to ensure all stations have a common operational picture. A combination of low throughput and high volumes of traffic will resort in a greater number of frame collisions.

C. IRIDIUM SATELLITE CONNECTIONS

Remote sensor networks have become popular in recent years and will have increasing use in military operations around the globe. These sensors may require remote systems to manage their network connections based on changing combat conditions and sensor priority. SNMP provides the ability to monitor a network and identify issues before they can become catastrophic problems, as well as to change basic settings in the network configuration.

In the beginning, the Satellite Network Management team attempted to use the RS-232 MIB (OID 1.3.6.1.2.1.10.33) as a potential point of monitoring. While monitoring is possible, many of the available SNMP agents do not come with the MIB and cannot support it. Additionally, testing revealed that this MIB would only report the success of data flowing through the connection at Layer 1 (PHY). Unfortunately, the available SNMP agents did not carry the PPP-LCP MIB (OID 1.3.6.1.2.1.10.23) either, which the team hypothesizes would return monitoring information between the end node and the RAS server. The team was only left the possibility of monitoring of the IP MIB (1.3.6.1.2.1.4). The IP MIB however was able to provide some capability for providing detailed network information, and became the foundation for further tests.

Using SNMP over an Iridium data connection though is found to be a non-ideal solution. This is greatly due to its limited bandwidth capability of 2400 bps. The polling interval that is normally used for SNMP enabled agents on the TNT network can not be used for the Iridium satellite communication devices due to the extremely low bandwidth that is available. Instead a longer polling period must be utilized so not to saturate the communication link between Solarwinds and the remote sensor network. Additionally, the end node appears to not accept SNMP or ICMP requests when transferring operational data across the network. A more ideal solution would be to place these

sensors on higher throughput networks as satellite antenna technology continues to improve.

D. TACSAT

Due to the primary mission of TacSat, usage of these satellites will be similar in nature to the stand alone OSCARs. Since these satellites are designed to change their orbits, weight is a primary consideration in the satellites' design. Thus, the Satellite Network Management team would only recommend that a store and forward capability be added, which could use the same storage space that captured image data resides. Quality of Life data, such as sports scores or other news, could be recorded at the control stations and transmitted over occupied areas. As the satellite requires the space for imagery, the Quality of Life data can be erased to make room.

E. RECOMMENDATIONS FOR FUTURE RESEARCH

Any of the focus points discussed here in would make excellent topics for further research. Specific topics are mentioned below.

1. APRS Mesh Networks for Field Units

The Monterey County APRS mesh experimented that a limited mesh is indeed possible in APRS. As discussed before, however, the current WIDEN-n protocol only allows for a maximum of seven hops, meaning that the mesh can only guarantee nine users the common operational picture.

CENETIX currently possesses ten Kenwood TH-D7a handheld APRS radios. While these radios are capable of performing as end nodes in a star network, they cannot fully participate in a mesh due to the lack of digipeater capability in the radios' TNCs.

A future research opportunity would be to modify the APRS protocol to accept a new path, which may be called "Mesh". This new path would be defined by the following steps:

- Each station would remember its neighbors, based off of position reports.
- Upon receiving a frame, the station would choose a random wait period.
- If the station detects within the wait period that all its neighbors did not digipeat the frame, then it would digipeat.

- The station would have a fixed time it would remember the frame, in order to not repeat it in future receptions

The radios would perform this task by connecting them with either notebook computers or PDAs, and modifying existing APRS software in the computer. The radios themselves would be in the Packet TNC mode, and the TNC would communicate with the computer using the KISS instruction set.

The development of this protocol should be reported to the APRS working group for official integration into the APRS protocol.

2. APRS and Internet Gateways

With APRS proven to be a robust SA tool, it does have some limitations and the most important is range. Amateur radio operators overcome this problem through the uses of Internet Gateways (IGATE) to connect different APRS networks across the world and to minimize traffic that must be carried on RF to deliver position and message data. IGATEs connect to APRS servers, which serve as central repositories for APRS data, and provide for World Wide Web and APRS client access. The Satellite Network Management group employed IGATEs in this manner to display experiments over the World Wide Web to interested parties otherwise unable to receive the RF data.

Should a military unit employ APRS on military frequencies, they may wish to employ a similar solution over a military network of appropriate classification. Future study could determine what steps would be required to establish such a system, how it could best be used in field environments, and whether its database could be redesigned to feed into the Global Command and Control System (GCCS).

3. SINCGARS (Single Channel Ground and Airborne Radio System) with ARPRS

SINCGARS tactical radios have the capability to frequency hop across the radio frequencies of 30 MHz to 87.975 MHz. The frequency hopping provides a defense against jamming by adversaries. SINCGARS is not just for voice communications it also has a 16 Kbps data capability that is useful to tactical users.[75] The radios can be used with a backpack, mounted in a vehicle, or mounted in an aircraft. The integration of

[75] "Advanced SINCGARS Improvement Program Family of Radios", [web site] (cited 17 FEB 06); available from World Wide Web @ http://www.acd.itt.com/pdf/ASIP_Family.pdf

SINCGARS and APRS could provide a potential solution for field users in a tactical environment. The radio would act as an interface for the APRS packet data to report SA information while provide the users with the security of frequency hopping.

4. Common Object Request Broker Architecture (CORBA) with Remote Sensor Networks and Iridium

From the experiments involving the Iridium data connection and the Solarwinds Network Management Software, it was discovered that the 2400 bps link is just too small to allow the full use of SNMP. A recommendation and an area for future study is to have CORBA, a middleware development application, provide an interface between the remote sensor network and Solarwinds.

As envisioned, CORBA would allow Solarwinds to monitor the Iridium connection and not saturate the link until it is disengaged. CORBA would allow this by acting as the intermediary between the two. Solarwinds would send an SNMP get request to the sensor network. CORBA would note the request and when the computer sends the requested information across the Iridium connection CORBA would step in. CORBA would strip off the predefined information that is deemed most valuable and send that information to across the Iridium connection, then save the remaining data locally for later analysis. This amount of information is speculated to be considerably less than the information that would be sent across the connection without CORBA in place.

5. D-STAR Over Satellite

D-STAR, an open protocol published by the Japan Amateur Radio League and implemented in several Icom radios, is a state-of-the-art integrated digital voice and data mode over amateur radio.[76] It provides for automatic routing of private calls, position information, and up to 128 Kbps data across the network. Data connection is provided by either a RS-232 or USB 1.0 connection for low speed data, and by Ethernet port (RJ-45) for high speed data. While higher throughput rates are available on 1.2 GHz systems, it

[76] "What is D-Star?" [web page] (cited 17 FEB 06); available from World Wide Web @ http://www.icomamerica.com/amateur/dstar/dstar2.asp

will also operate on the 144 MHz and 440 MHz bands.[77] A D-PRS server attached to a D-STAR Repeater can IGATE to position data to the APRS network.[78]

Over the long term, D-STAR would provide a better backup to the TNT backbone than APRS due to its increased data ability and integrated voice capability. Additionally, D-STAR has never been tested in space yet. One recommendation for future study would be to integrate D-STAR into a future satellite, and test its ability to operate in orbit.

6. PPP-LCP MIB

The PPP-LCP MIB offers tremendous potential when monitoring future satellite links. Iridium and many other satellite links use PPP as the Layer 2 protocol between the end node and the gateway. Any network problems due to poor satellite connectivity will be identified through monitoring PPP. Future research for this protocol would include implementing a SNMP agent capable of monitoring the PPP MIB on the deployable sensor cluster computers, determining if DIRECWAY uses PPP, and if the DIRECWAY modem has an SNMP agent installed for Nemesis link analysis.

[77] "Technical Specifications" [web page] (cited 17 FEB 06); available from World Wide Web @ http://www.icomamerica.com/amateur/dstar/dstar7.asp

[78] "Applications" [web page] (cited 17 FEB 06); available from World Wide Web @ http://www.icomamerica.com/amateur/dstar/dstar5.asp

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